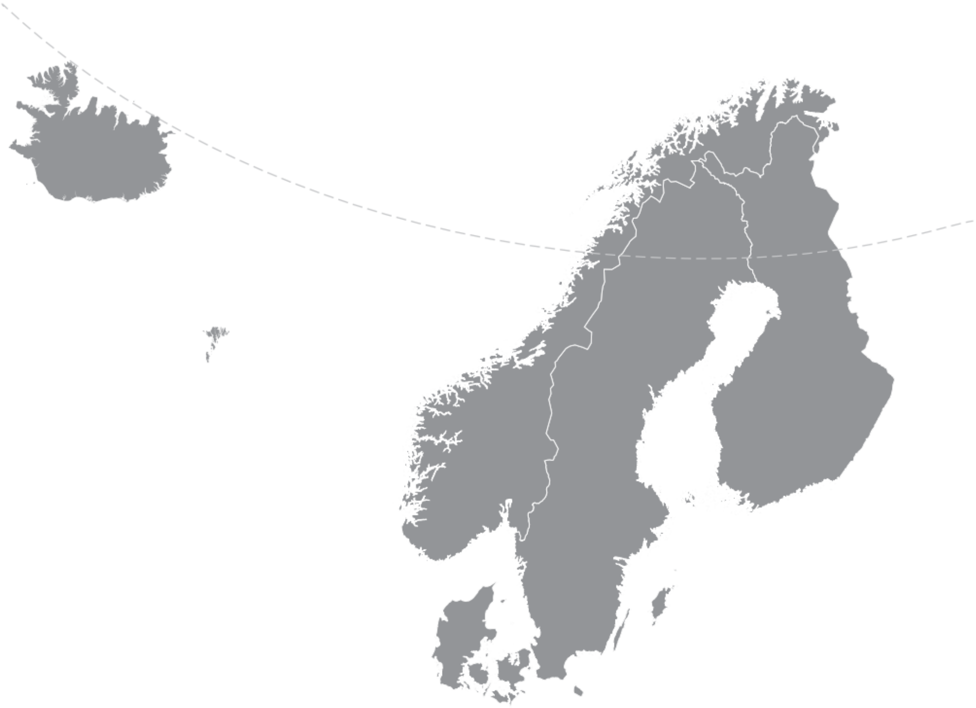
THE NORDIC CONCRETE FEDERATION 2019 Workshop Proceedings No. 15

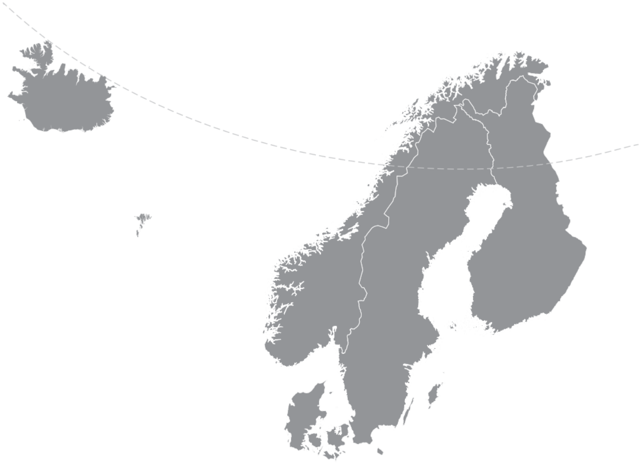
Structural lightweight aggregate concrete

WORKSHOP PROCEEDINGS FROM A NORDIC WORKSHOP

Trondheim - Norway, February 20th, 2019



Structural lightweight aggregate concrete



WORKSHOP PROCEEDINGS NO. 15

FROM A

NORDIC WORKSHOP

Trondheim, Norway

February 20th, 2019

Nordic
Concrete
Federation

PREFACE

The Nordic mini-seminar: Structural lightweight aggregate concrete has been organized under the auspices of the ongoing Norwegian research project; Durable Advanced Concrete Structures (DaCS). The research project DaCS looks to increase the knowledge of sustainable and competitive reinforced concrete structures in harsh environment and is funded by The Research Council of Norway, in addition to several industrial partners. The DACS partners are Kværner AS (project owner), Axion AS (Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens vegvesen), Norwegian University of Science and Technology (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS. One of the ongoing activites related to the aforementioned research projects is the PhD project entitled "*Ductility of lightweight aggregate concrete structures"* carried out by Jelena Zivkovic.

The seminar is to be hosted by NTNU, Institute for materials and structures. The main goal is to increase the knowledge of structural lightweight aggregate concrete and to provide exchange of information and further development among the participants. This booklet documents the collection of extended abstracts of all the given lectures during the seminar. The organizing committee would like to thank all the speakers and contributors at the seminar, and the financial support of the research project DaCS and Stalite lightweight aggregate Company from USA.

Trondheim, February 2019.
Terje Kanstad, Jan Arve Øverli (ed.) and Jelena Zivkovic (ed.)

CONTENTS:

Preface i

Participants iii

Program iv

KEYNOTE LECTURES

Tor Arne Hammer
Structural LWAC – mix design, material properties and production 2

Christian Thienel
Application of Lightweight Concrete 6

Reid Castrodale
Behaviour and Design of Structural LWC in USA 10

SEMINAR LECTURES

Jody R. Wall
Production and Physical Properties of Expanded Slate Lightweight Aggregate 17

Arianna Minoretti, Simen Hellgren Holtberget, Bernardo Costa, Johannes Veie
Lightweight concrete for the E39 fjord-crossing project in Norway 21

Kjell Tore Fosså
LWAC concrete in offshore structures 25

Hans Stemland
Spalling of concrete cover to reinforcement in high strength LWA concrete (just presentation)

Jelena Zivkovic and Jan Arve Øverli
Failure of lightweight aggregate concrete under compressive strain gradients 29

Jelena Zivkovic, Seyed Mohammad Javad Razavi, Filippo Berto and Jan Arve Øverli
Effect of loading rate on the fracture energy of lightweight aggregate concrete subjected to three-point bending test 33

PARTICIPANTS

	Name	Organization	Country
1	Mikael Basteskår	Kværner AS	Norway
2	Kjell Tore Fosså	Kværner AS	Norway
3	Andrei Shpak	NTNU	Norway
4	Jelena Zivkovic	NTNU	Norway
5	Jan A Øverli	NTNU	Norway
6	Terje Kanstad	NTNU	Norway
7	Hans Stemland	NTNU	Norway
8	Torbjørn Heitmann Valum	Axion AS	Norway
9	Rolf Valum	Axion AS	Norway
10	Filippo Berto	NTNU	Norway
11	Javad Razavi	NTNU	Norway
12	Tor Arne Hammer	SINTEF	Norway
13	Reid Castrodale	Stalite Company USA	USA
14	Christian Thienel	München University	Germany
15	Xavier Kestemont	ARGEX	Belgium
16	Arianna Minoretti	NPRA/ Statens vegvesen	Norway
17	Holtberget Simen Hellgren	NPRA/ Statens vegvesen	Norway
18	Veie Johannes	NPRA/ Statens vegvesen	Norway
19	Josef Kiendl	NTNU	Norway
20	Jody Wall	Stalite Company USA	USA
21	Kyle Weatherly	Stalite Company USA	USA
22	Claus Vestergaard Nielsen	DTI	Denmark
23	Geir Norden	Leca	Norway
24	Stefan Jacobsen	NTNU	Norway
25	Daniel Cantero	NTNU	Norway
26	Kathrine Stemland	NTNU	Norway
27	Pamela Zuschlag	NTNU	Norway
28	Gunrid Kjellmark	SINTEF	Norway
29	Yannick Martin Anton	SINTEF	Norway
30	Elisabeth Leite Skare	NTNU	Norway

PROGRAM

Seminar lasted for one day and it was divided in three sessions that are listed below:

1) Material (general about lightweight aggregates that are used for LWAC production)
2) Application of lightweight aggregate concrete (LWAC)
3) Structural behavior of lightweight aggregate concrete

Day 1		
8:45	**Registration**	
9:00	Opening of the seminar, introduction and presentation of DaCS project Practical information	**Jan Arve Øverli**, NTNU and **Jelena Zivkovic**, NTNU
9:15	**Session 1 - Material (general about lightweight aggregates that are used for LWAC production)**	
Moderator: Jan Arve Øverli		
9:15	Structural LWAC – mix design, material properties and production (Keynote, 30 min)	**Tor Arne Hammer**, SINTEF
9:55	Production and Physical Properties of Expanded Slate Lightweight Aggregate (15 min)	**Jody R. Wall**, Carolina Stalite Company
10:10	**Break (Coffe + water)**	
10:30	**Session 2 - Application of lightweight aggregate concrete (LWAC)**	
10:30	Application of Lightweight Concrete (Keynote, 30 min)	**Christian Thienel**, Institut für Werkstoffe des Bauwesens, Universität der Bundeswehr München
11:10	Lightweight concrete for the E39 fjord crossing project in Norway (15 min)	**Arianna Minoretti, S.H. Holtberget, B. Costa, J.Veie**, Norwegian Public Roads Administration
11:30	**Lunch break**	
12:30	**Session 2 - Application of lightweight aggregate concrete (LWAC)**	
Moderator: Terje Kanstad		
12:30	LWAC concrete in offshore structures (15 min)	**Kjell Tore Fosså**, Kværner AS
12:50	**Session 3 – Structural behavior of lightweight aggregate concrete**	
12:50	Behavior and Design of Structural LWC in USA (Keynote, 30 min|)	**Reid Castrodale**, Carolina Stalite Company, ESCSI Institute, Castrodale Engineerring Consultants
13:30	**Break (Coffe + water)**	
14:15	**Session 3 – Structural behavior of lightweight aggregate concrete**	
14:15	Spalling of concrete cover to reinforcement in high strength LWA concrete (15 min)	**Hans Stemland**, NTNU / SINTEF
14:40	Failure of lightweight aggregate concrete under compressive strain gradients (15 min)	**Jelena Zivkovic ,** NTNU
15:05	Effect of loading rate on the fracture energy of lightweight aggregate concrete subjected to three-point bending test (15 min)	**Seyed Mohammad Javad Razavi ,**NTNU
15:30	**Break (Refreshments)**	
16:00	Closing of the seminar	**Terje Kanstad**, NTNU
End of Workshop / Nordic mini seminar		

KEYNOTE LECTURES

Structural Lightweight aggregate concrete – mix design, materials properties and production

Tor Arne Martius-Hammer
Senior Researcher, Dr.Philos
SINTEF Building and Infrastructure
7465 Trondheim, Norway
e-mail: tor.hammer@sintef.no

ABSTRACT

The paper discusses some peculiarities of lightweight aggregate concrete (LWAC) that is important to be aware of concerning mix design, LWAC properties and LWAC production, and how this is taken care of in specifications given in present European standards. It includes discussion of influence of the porous nature of LWA that results in high water absorption as well as low strength and E-modulus.

Key words: Concrete, lightweight aggregate, mix design, properties, production.

1. INTRODUCTION

Structural lightweight aggregate concrete (LWAC) is defined according to ModelCode 2 as: *"Concrete having closed structure and a density* $\leq$ *2200 kg/m*^{3} *with a portion of artificial or natural lightweight aggregate (LWA) having a particle density < 2000 kg/m*^{3}*"*. EN 206-1 classifies LWAC in six density classes, ranging from 800 to 2000 kg/m^3 (oven dry). Normally, it is the coarse fraction of the aggregate that is exchanged by LWA. A further density reduction can be achieved by replacing the sand fraction (or a part of it) with LW sand. This is not discussed in the present paper. More information can be found in [1].

According to EN 13055 "Lightweight aggregates", LWA may be from the following origin:

- Natural aggregates, i.e. Pumice and Scoria
- Aggregates manufactured from natural materials and/or from by-products of industrial processes, like from clay (i.e. Leca, Liapor), shale/slate (i.e. Stalite) and recycled glass (i.e. Liaver, Poraver)
- By-products of industrial processes, i.e. fly ash (i.e."Lytag") and blast furnace slag

LWAC structures may be designed according to the same rules as normal density concretes, with some given additional requirements (Modelcode 2). Also, execution as well as specification, performance, production and conformity, are taken care of in EN 13670 and EN 206-1, respectively. The present paper discusses some peculiarities of LWAC that is important to be aware of concerning mix design, properties and production. It is mainly related to the porous nature of LWA that results in high water absorption as well as low strength and E-modulus.

2. MIX DESIGN

2.1 Density and compressive strength

LWA introduces an additional dimension in mix design; density. Hence, LWA fitting the concrete density requirement but without comprising the compressive strength requirement, must be found. Figure 2 shows guiding achievable strength-density combinations for LWAC with LWA of various particle densities. Since LWA have normally significantly lower strength than the cement paste/mortar, the strength potential of LWAC depends of course on the strength potential of the LWA used. The limited strength potential of LWA (bulk densities of 700 and 800 kg/m^3, respectively) is demonstrated in Figure 1, showing the relation between the effective water to cement + silica fume ratio (w/(c+s)) and the compressive strength of LWAC [2]. Similar relations may be obtained for any type of LWA. As can be seen, the strength follows then a progressively decreasing curve with decreasing w/c rather than the opposite as well known for normal concrete. Also, note that since a reduced w/c increases the density of the concrete (increased density of the cement paste), a further reduction of w/c may lead to a reduction of the strength /density ratio.

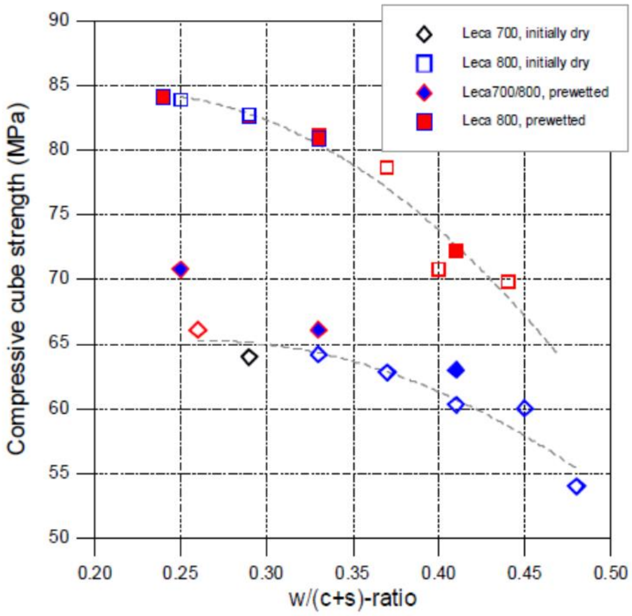


Figure 1 - The compressive cube strength of LWC as a function of the effective w/(c+s)- ratio. The LWA is of the Leca type, having bulk densities of 700 kg/m^3 and 800 kg/m^3 respectively [2]

To increase the strength to density of the concrete it is appealing to increase the content of the LWA having the sufficient strength potential. It implies a corresponding reduction of the volume of natural sand. This gives a concrete with a rather low mortar content, and therefore a risk of segregation. To avoid segregation, the mortar phase then should be more cohesive and viscous than normal. This may be obtained using natural sand with a high fines content, a low w/c-ratio, high amounts of silica fume, or even stabilising chemical agents.

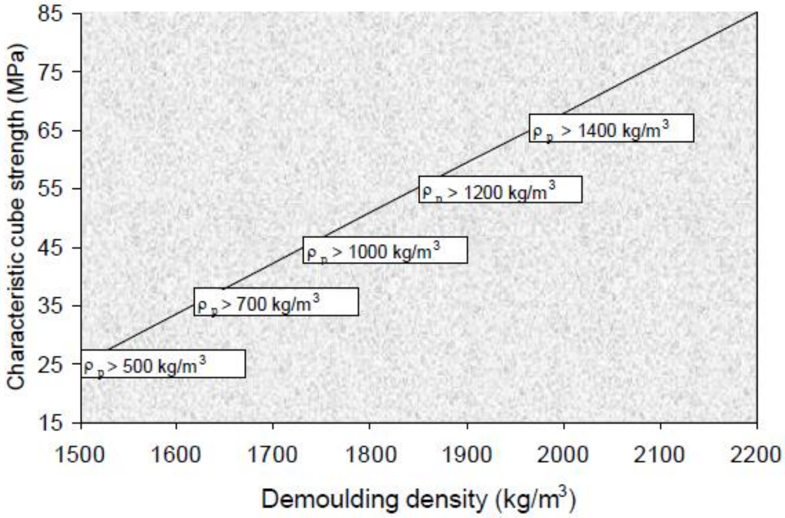


Figure 2 – Guiding achievable strength-density combinations for LWAC with LWA of various particle densities (ρ_p) LWA in coarse fractions only [3].

2.2 Effective water content and water to cement ratio

EN 206-1 gives limits for w/c related to exposure classes. The same limits apply also for LWAC. The water-binder ratio shall be based on the effective water content of the mix. The effective water content is defined as the total water content (incl. possible surface water of the aggregates) minus the sum of initial water content of the aggregates and the mix water absorbed by the aggregates at the time of initial setting. Since LWA has a high water absorption potential, determination of the effective w/c is challenging if the LWA is not in a homogenous water saturated condition before mixing. Also, such a condition influences workability as the LWA may absorb some mix water during the fresh state of the concrete. Hence, there is a need to find the portion of mix water absorption by the LWA.

The mix water absorption does not only depend on the degree of saturation, but also the state of moisture, i.e. whether the LWA is in a drying or wetting state. Figure 3 shows that the absorption in LWA at a given moisture content varies with the state of moisture distribution within the LWA particles [4]. Typical for LWA in a drying phase is a dry surface and a concentration of moisture in the core, see Figure 3. Then, LWA will have a higher absorption of mix water than if the LWA is in a soaking phase, i.e. a high moisture content in the surface area and a relatively dry inner core.

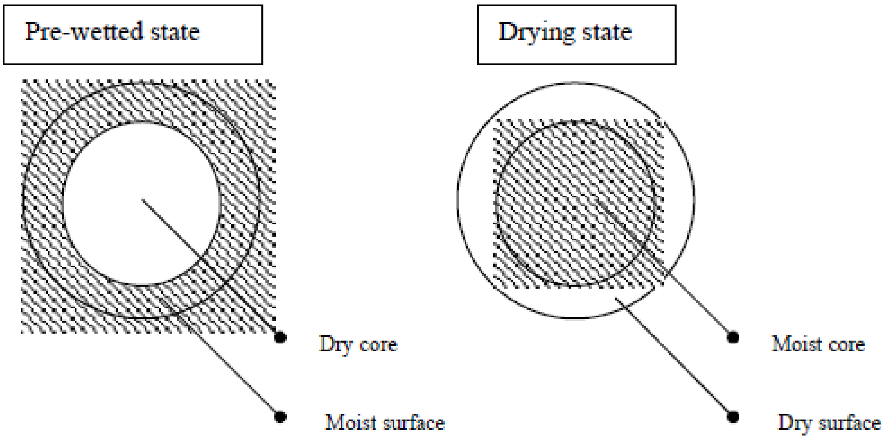


Figure 3 – Two principal moisture conditions of light weight aggregates [4]

Tests reported in [4] show that one hour absorption might vary as much as 5 % (points) depending on distribution within the particles. This corresponds to about 20 litres of mix water / m^3 for a typical LWAC based on this aggregate. Hence, to ensure uniform properties during production of LWAC for a structure, determination of absorption properties of the LWA in the actual moisture condition is needed.

So, if the LWA used is not in a homogenous water saturated condition when mixed in the concrete, the mix water absorbed in the LWA at the time of initial setting, w_{abs}, shall be determined as:

$$w_{abs} = 1.0 * w_{1hm}$$

Where w_{1hm} is determined according to prEN 1097-6 appendix "C" with the following two modifications; a) The initial moisture content and condition shall be the same as for the LWA actually used in the concrete production, b) w_{1hm} is measured after one hour immersion

3 PRODUCTION

The main difference from normal density concrete in production is the vulnerability towards pumping. This is because the pumping pressure may squeez mix water into the LWA and when the pressure is released (i.e. during placing) some of the water may come out again (due to compressed air in the LWA), and also air bubbles may evacuate simoutaneously and agglomerate on the LWA surface. It may result in decreased strength and increased in permeability, the latter potentially detrimental to the durability properties [5]. Therfore, EN 13670 requires: "*When LWAC is to be pumped, documentation shall be available showing that pumping will have no significant effect on the strength of the hardened concrete.*"

REFERENCES

[1] Structural LWAC Specification and guideline for materials and production. European Union – Brite EuRam III project; EuroLightCon Economic Design and Construction with Light Weight Aggregate Concrete. Document BE96-3942/R14, May 2000.

[2] Smeplass S.: Lightcon DP2 Materialegenskaper, Delrapport 2.9: Effekt av masseforhold på lettbetongs trykkfasthet, (Effect of the w/c -ratio on compressive strength og LWAC), SINTEF-report STF70 A97829, Trondheim 1997.

[3] Norsk Betongforenings Publikasjon nr. 22: Lettbetong, Spesifikasjoner og produksjonsveiledning, (Norwegian Concrete Association’s Publication no. 22: LWAC, Specification and production guideline), Norwegian Concrete Association, Oslo, Norway, 1999.

[4] Smeplass S.: LettKon Report 4.5: Resultater fra laboratorieforsøk på lettilslag og lettbetong, (Results from laboratory testing on LWA and LWAC), SINTEF-report STF22 A99751, Trondheim 1999.

[5] Helland S. and Maage M.: Strength Loss in Un-remixed LWA Concrete, Proceedings of the International Symposium on Utilization of High Strength Concrete, Lillehammer, June 1993.

Application of Lightweight Concrete

Karl-Christian Thienel, Univ.-Prof. Dr.-Ing.
Department of Civil Engineering and Environmental Sciences
Institute for Construction Materials
Bundeswehr University Munich
Werner-Heisenberg-Weg 39
85579 Neubiberg, Germany
e-mail: christian.thienel@unibw.de

ABSTRACT

A brief survey is given of various applications of structural lightweight concrete (LC) covering the entire range of densities.

Keywords: Lightweight concrete, LC, self-compacting lightweight concrete, SCLC, infra-lightweight concrete, ILC, lightweight aggregate, LWA, thermal conductivity; lightweight sand.

1 COMBINATIONS OF STRENGTH AND DENSITIY CLASSES OF LIGHTWEIGHT CONCRETE

Structural lightweight concrete (LC) is a very versatile material due to the combination of sufficient strength with a minimum of structural weight. Depending on the intended use the focus is either primarily on load bearing capacity and a corresponding minimum density as it is the case e. g. for bridges or offshore structures. On the other hand the focus is on reducing the thermal conductivity of LC while providing only a necessary minimum strength as for instance in the case of external fair faced concrete walls for private houses. Irrespective of the intended use both, strength and density are somewhat connected and need to be considered in equal measure. Fig. 1 gives an impression of the correlation between strength classes for LC and the necessary dry density according EN 206 [1].

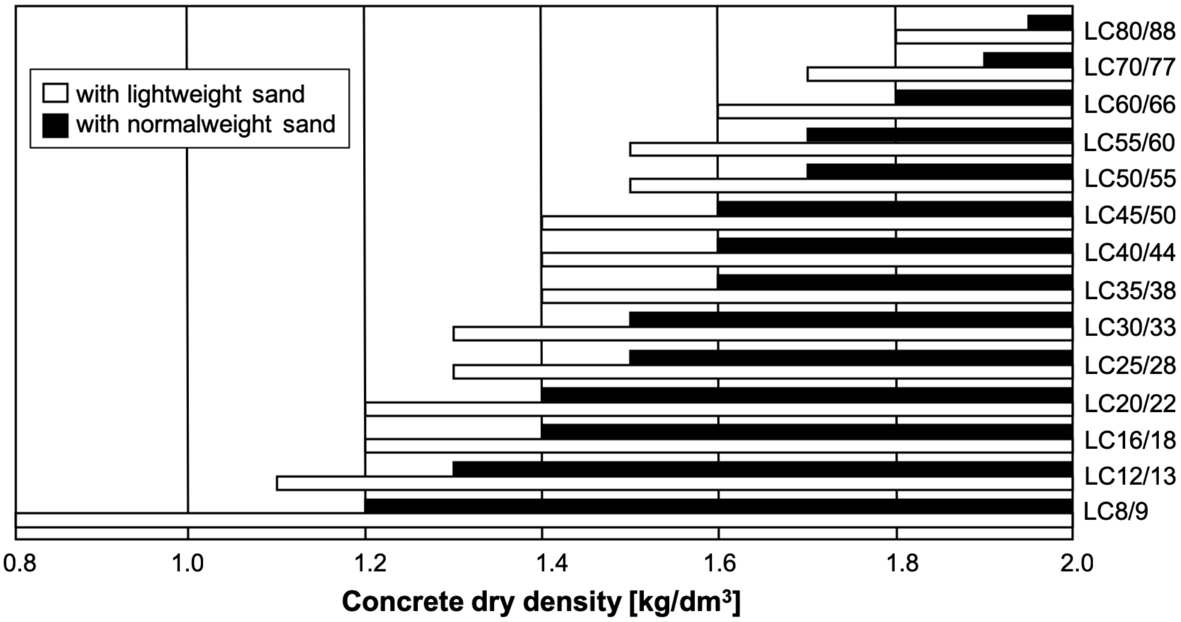


Figure 1 – Correlation between strength classes and necessary dry density for LC. Based on [2]

2 CLASSIFICATION OF APPLICATION AREAS FOR LIGHTWEIGHT CONCRETE

Lightweight concrete for structural applications is often made with normal weight sand. The density exceeds in most cases 1.4 kg/dm^3. Thus far, only a few projects have been made with self-compacting lightweight concrete (SCLC). Three different application and synergetic areas exist for light and very light concrete made with lightweight sand. They depend mainly on the combination of required compressive strength and thermal conductivity needed in order to adapt to the building physics requirements [3].

- Highly stressed facades of office buildings with many and wide window and door openings demand a higher compressive strength and are realized in a concrete density range between 1.3 and 1.6 kg/dm^3.
- Less stressed facades, which either have thicker walls, less stories or less openings are executed in the density range between 1.0 and 1.3 kg/dm^3.
- Very light LC with the best thermal insulation are increasingly used for exclusive private houses. Their external walls are executed in densities ranging from 1.0 down to 0.80 kg/dm^3 and even less. Below 0.80 kg/dm^3 such lightweight concretes are no longer covered by existing standards for structural lightweight concrete in Europe. Since the thermal insulation requirements lead to rather thick walls, the achievable strength is usually high enough to provide sufficient load bearing capacity for single- or two-story houses. In some projects, the concrete strength is even below a strength class LC8/9, which is the lowest strength class that is covered by existing standards for LC [1]. These so-called infra-lightweight concretes (ILC) [4] range somewhere in between structural lightweight concrete (LC) and no-fines lightweight concrete with open porous structure (LAC). Special considerations are necessary regarding a suitable design concept and durability for ILC. Thus ILC require a technical approval or an approval on an individual basis [5].

3 EXEMPLARY PROJECTS

3.1 LC made with normal weight sand and in the density range above 1.5 kg/dm^3

A white LC35/38 D1.6 forms the curved roof that rests on individual columns and covers the bus and railway station in Korbach, Germany (Fig. 2 left). The pedestrian bridge crossing the river Vitava in České Budějovice (Budweis), Czech Republic, has a main span of 75 m and consists of 54 precast elements made with LC35/38 D1.8 (Fig. 2 right). The elements rest on two sets of cables and form the bridge deck.

Figure 2 – Left: Bus station roof, Korbach, Germany. Right: Pedestrian bridge Budweis, Czech Republic

3.2 Self-compacting lightweight concrete (SCLC)

SCLC was used for the first time in 2002 for the lower (Fig. 3 left) and upper end elements of the upper tribune in the football stadium “Volkswagen Arena” in Wolfsburg, Germany. The architects asked for a perfect fair faced concrete. This could only be accomplished through a self-compacting LC25/28 D1.6 due to the complex shape of the precast elements. In 2005 the Emmaus Autobahn Chapel (Fig. 3 right) was built using a technical approval for a LC35/38 D1.3 named “LiSA”. Such technical approval is still needed as SCLC is not covered by European concrete standards.

Figure 3 – Left: lower end element of the upper tribune, Volkswagen Arena, Wolfsburg, Germany. Right: Emmaus Autobahn chapel, rest and service area Hegau-West, Germany.

3.2 LC made with lightweight sand and in the density range above 1.3 kg/dm^3

Thermal conductivity is still too high for using LC with densities above 1.3 kg/dm^3 as sole insulation material for external walls. Here, the excellent combination of strength and density is important. A black-colored LC16/18 D1.4 formed the outer shell of the external sandwich walls of the apartment and office building L40 (Fig. 4 left) and reduced the weight of the cantilevering facing. Even more severe were the requirements for the concrete hull of the heavy lifter [6] (Fig. 4 right). A LC35/38 D1.4 was chosen as a demolding density below 1600 kg/m^3 was mandatory for the necessary buoyancy.

Figure 4 – Left: Linienstraße 40, Berlin, Germany. Right: Heavy lifter, Rotterdam, The Netherlands

3.4 LC made with lightweight sand and in the density range between 1.0 and 1.3 kg/dm^3

Less stressed facades which either have thicker walls, less stories or less openings are executed in the density range between 1.0 and 1.3 kg/dm^3. These LC are commonly used for office buildings and public structures like churches. The regional and district court in Frankfurt/Oder, Germany, was built using LC16/18 D1.2 for its fair faced concrete (Fig. 5 left). A LC12/13 D1.2 formed the external 60 cm thick monolithic walls of the *new office building of Spenner GmbH & Co. KG in Erwitte, Germany* (Fig. 5 right).

Figure 5 – Left: Regional and district court Frankfurt/Oder, Germany. Right: Office building, Erwitte, Germany

3.5 ILC made with lightweight sand and dry densities below 0.8 kg/dm^3

Currently the most prominent executed examples for ILC in Germany are two private houses. The first achieved a strength of 7,4 MPa at a density of 0.76 kg/dm^3 (Fig. 6 left) and a more recent building a record breaking LC8/9 D0.725 (Fig. 6 right).

Figure 6 – Left: Private house Schlaich, Berlin, Germany. Right: Private house Thalmair. Aiterbach, Germany

4 REFERENCES

[1] DIN EN 206. *Concrete - Specification, performance, production and conformity*. 2013, p. 96.

[2] Thienel, K.-C., *Besonderheiten bei Leichtbeton in DIN FB 100*, in *Heft 526 Erläuterungen zu den Normen DIN EN 206-1, DIN 1045-2, DIN EN 13670, DIN 1045-3, DIN 1045-4 und DIN EN 12620*, Deutscher Ausschuss für Stahlbeton, Editor. 2011, Deutscher Ausschuss für Stahlbeton: Berlin. pp. 80-84.

[3] Thienel, K.-C., *Structural lightweight concrete for external walls – A challenge between the poles of improved thermal insulation and fair faced concrete* ALITinform: Cement. Concrete. Dry Mixtures, 2018. 50(1): pp. 18-29.

[4] Schlaich, M.; Zareef, M.E., *Infraleichtbeton.* Beton- und Stahlbetonbau, 2008. 103(3): pp. 175-182.

[5] Callsen, B.; Thienel, K.-C., *Besondere Aspekte bei der Entwicklung und Ausführung eines hochwärmedämmenden Hochleistungs-Leichtbetons mit sehr niedriger Betonrohdichte.* Beton, 2017. 67(4): pp. 128-134.

[6] Thienel, K.-C., *Heavy Lifter – Konstruktion und Bautechnik.* Beton, 2011. 61(6): pp. 224-229.

Nordic mini-seminar: Structural lightweight aggregate concrete
Trondheim, Norway, February 20th, 2019

Behaviour and Design of Structural LWC in USA

Reid W. Castrodale, PhD, PE
Castrodale Engineering Consultants, PC
Concord, North Carolina, USA
e-mail: reid.castrodale@castrodaleengineering.com

ABSTRACT

Lightweight aggregates manufactured in the USA differ from European aggregates and as a result, properties of lightweight concrete vary. Selected mechanical properties of lightweight aggregate and lightweight concrete in the USA are discussed, with focus on properties of expanded slate from North Carolina (STALITE). Several differences in structural design practice between the USA and Europe are discussed that are related to lightweight concrete design.

Key words: Lightweight aggregate, lightweight concrete, design, material properties, durability.

1. INTRODUCTION

Structural lightweight aggregate can be used to make high performance structural lightweight concrete. Such material has been used in major structures in the USA and in Europe [1]. As structural engineers attempt to develop ever more creative and aggressive designs, lightweight concrete continues to be a good solution to improve both structural efficiency and durability of structures, contributing to the success of some of the boundary pushing designs, as well as many more ordinary projects, including both new construction and rehabilitation projects.

Designers are often not familiar with the properties of structural lightweight aggregate and lightweight concrete. Many engineers are sceptical about whether lightweight concrete can be a durable material for structures that must have a long service life with low initial and long-term costs. For this workshop, it is also important to introduce designers in Europe to lightweight aggregates produced in the USA, and to the ways in which lightweight concrete is addressed in the codes in the USA.

This paper is intended to begin to address these issues by briefly discussing lightweight aggregate in the USA, with specific details given for the expanded slate lightweight aggregate manufactured in North Carolina (STALITE). Design of lightweight concrete structures in the USA is then discussed, including several recent changes in the bridge design code related to lightweight concrete. Some of the differences between design codes in the USA and Europe related to this discussion of lightweight concrete are noted. A few properties of lightweight concrete used in the USA are then presented, again focusing on experience with STALITE aggregate.

2. LIGHTWEIGHT AGGREGATE IN USA

Structural lightweight aggregate in the USA is produced using shale, clay and slate [2]. The raw material is expanded at high temperatures in a rotary kiln to produce a porous structural lightweight aggregate. Properties of the lightweight aggregate vary between sources, but structural lightweight concrete can be produced using aggregate from all sources. The bulk density of coarse lightweight aggregate ranges from about 720 to 880 kg/m^3, and from about 960 to 1120 kg/m^3 for fine aggregate. The largest lightweight aggregate grading used in the USA is 19 mm. Water absorption of lightweight aggregates ranges from 6% to more than 25% by mass. Most pores in the aggregate are not connected. For more consistent workability and hardened properties, lightweight aggregate is generally prewetted prior to batching.

2.1 STALITE Lightweight Aggregate

STALITE is a high-performance lightweight aggregate manufactured in North Carolina, USA, by expanding a meta-argillitic slate [3]. After firing and cooling, the aggregate is crushed and screened to obtain the desired particle sizes. The aggregate has the lowest absorption and highest strength of lightweight aggregates available in the USA. The dry bulk density of STALITE ranges from about 770 to 830 kg/m^3 for coarse gradations to 960 kg/m^3 for fine gradations with dry relative densities ranging from about 1.50 for coarse aggregate to 1.70 for fine aggregate. These values are generally higher than other lightweight aggregates in the USA.

The typical absorption (by mass) to a “wetted surface dry” condition is 6% for the 19 mm grading, 7% for the 12.5 and 9.5 mm gradings, and 12% for the fine grading (4.75 mm-0). This low absorption, thought to be the lowest in the world, is a characteristic of the aggregate and is achieved without applying sealing materials or prohibiting crushing of the aggregate after firing. Analysis demonstrates that only about 20% of the pores in coarse aggregate particles and nearly 50% in fine aggregate particles are filled with water when in the “wetted surface dry” condition [3] – the remaining pores are disconnected and remain unfilled.

It seems reasonable to expect lightweight aggregate, because of its porous nature, to have low abrasion resistance. However, test results indicate that STALITE has Los Angeles Abrasion loss values (AASHTO T 96) approximately equal to the average computed for all conventional aggregates on the North Carolina transportation agency approved aggregate list [3].

3. LIGHTWEIGHT CONCRETE IN US DESIGN CODES

Several differences in structural concrete design practice between the USA and Europe related to lightweight concrete are discussed, along with some recent changes in the US bridge design code.

3.1 Compressive and Tensile Strengths of Concrete

US design codes [4,5] use the minimum specified design compressive strength of cylinders rather than the characteristic strength of cubes or cylinders, so nearly all compressive strength data generated in the USA are for cylinders. Concrete producers use assumed or experience-based mix variabilities to determine strengths required to reliably meet the design compressive strength.

Tensile strength of concrete is based on either the modulus of rupture based on bending of beams or the splitting tensile strength based on splitting cylinders.

3.2 Density

Density of lightweight concrete in US design codes [4,5] is based on the definition of the equilibrium density of concrete, which occurs when the concrete reaches moisture equilibrium with its environment. This density is taken as an estimate of the concrete density in the structure in service. Procedures for determining equilibrium density by testing or by calculations based on mix proportions are given in ASTM C567. This approach differs from Eurocode 2 [6] which uses the oven dry density of concrete. Data on oven dry densities may be available for some projects in the USA because one procedure for computing equilibrium density is to obtain the oven dry density of a concrete specimen then add a fixed increment of density (48 kg/m^3). This approximation may not be accurate, especially for high-strength low-permeability mixes. For many projects in the US, the oven dry density may not be available since it is not specified.

In some cases, fresh densities are specified and used for design because, for low absorption aggregate such as STALITE, the difference between the fresh and equilibrium densities is small – often less than 50 kg/m^3, so it is considered to be negligible. For precast concrete elements, the fresh density is important because it will define the self-weight of an element for handling

3.3 Definition of Lightweight Concrete

Recently, the definition of lightweight concrete in the US bridge design code [4] has been revised to recognize that lightweight aggregate has been used to produce concrete in the range between traditional lightweight concrete and normal weight concrete. The new definition of lightweight concrete in the *AASHTO LRFD Bridge Design Specifications* [4] includes densities up to 2160 kg/m^3, which has also been defined as the lower limit of density for normal weight concrete. This is similar to the limit of 2200 kg/m^3 in Eurocode 2 [6].

In the past, types of lightweight concrete were also defined to identify the applicable modification factor for tensile related capacities. The lowest density concrete is “all-lightweight concrete” which contains only lightweight coarse and fine aggregate while “sand-lightweight” concrete contains lightweight coarse aggregate with normal weight fine aggregate. In the US, “sand-lightweight” concrete is much more widely used. However, for lightweight aggregate from different sources, concrete with these definitions could have significantly different densities. Furthermore, a designer often has no knowledge of the combination of aggregates that might be used to achieve a specified density. Therefore, definitions of lightweight concrete based on mix composition have been removed from the bridge design specifications [4,7]; a similar change is now being considered for the building code [5].

3.4 Concrete Density Modification Factor

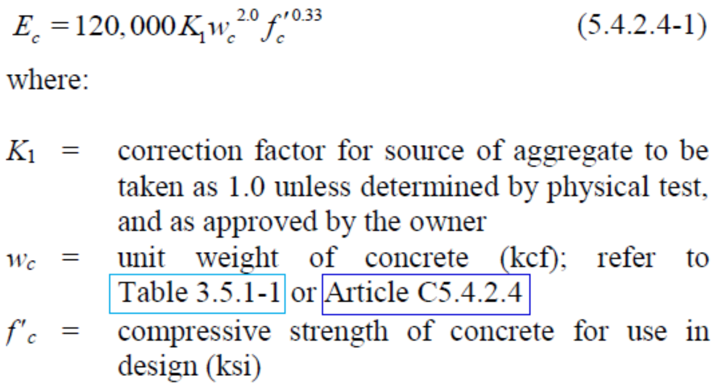
US design codes assume that lightweight concrete may have a reduced tensile capacity compared to normal weight concrete with the same compressive strength. This has been represented by what is now called the “concrete density modification factor”, λ, in the bridge code [4]. This factor is applied to $\sqrt{f_c'}$ terms in equations related to tensile strength of concrete, such as shear and development lengths. In the past, the factor was defined based on the all- and sand-lightweight concrete definitions, but it is now based on density [7]. It should be noted that recent studies have found lightweight concrete to have splitting tensile strengths equal to or greater than the expected tensile strengths for normal weight concrete [3,8], which means that a reduction factor is not needed. In the US bridge design code, the designer may specify the splitting tensile strength to be equal to the expected splitting tensile strength of normal weight concrete, in which case the factor λ will be 1.0 and no reduction will occur. It should also be noted that recent revisions to the bridge code [7] included the insertion of the concrete density modification factor into all equations where it should be used; previously, it was left up to the designer to apply the factor.

3.5 Resistance Factors

Resistance factors for strength design of concrete buildings have always been the same for lightweight and normal weight concrete [5]. However, when the AASHTO LRFD Specifications [4] were introduced in 1994, the shear resistance factor for lightweight concrete was 0.7, while a factor of 0.9 was used for normal weight concrete. This reduced resistance factor was in addition to the concrete density modification factor, so the reduction in shear capacity of lightweight concrete members was compounded. This presented a significant obstacle to the use of lightweight concrete for elements with a large shear demand. Following the collection and analysis of a significant body of test data on lightweight concrete, the resistance factor for shear for lightweight concrete has been increased and is now equal to the factor for normal weight concrete [7].

3.6 Modulus of Elasticity

The equation for estimating the modulus of elasticity of concrete in the AASHTO LRFD Specifications [4] has been revised to better predict values for lightweight and high strength mixes [7]. The new equation (in US units - ksi) is shown below and has been found to work well for several mixes using STALITE (constant is approximately 0.0017 for kg/m^3, MPa, and E_c in GPa).



$$E_c = 120,000 K_1 w_c^{2.0} f_c'^{0.33} \qquad (5.4.2.4\text{-}1)$$

where:

K_1 = correction factor for source of aggregate to be taken as 1.0 unless determined by physical test, and as approved by the owner
w_c = unit weight of concrete (kcf); refer to Table 3.5.1-1 or Article C5.4.2.4
f'_c = compressive strength of concrete for use in design (ksi)

3.7 Flexural Design at Ultimate Limit State and Stress-Strain Relationship

Current practice in the USA for computing flexural resistance of concrete elements at the strength limit state typically uses the approximate equivalent rectangular stress block rather than a stress-strain relationship. Because this is the prevailing design approach, recent data from testing stress-strain relationship parameters in the USA are not available. Tests have shown the approximate method to be conservative for lightweight concrete members [8].

4. PROPERTIES OF LIGHTWEIGHT CONCRETE

Only a few properties of lightweight concrete are discussed in the following, and even for these topics, adequate details cannot be presented because of space limitations. For more information on these and other properties of lightweight concrete, nearly all cited references provide data on properties of lightweight concrete, including STALITE.

Because of the differences in design approach between the USA and Europe, some concrete properties used in European practice are not discussed because they have not been investigated in the USA.

4.1 Compressive Strength and Density

Design compressive strengths for concrete made with STALITE can be as high as 73 MPa with single cylinder breaks as high as 90 MPa [9]. The maximum allowed fresh density of this concrete mixture, which was used for pretensioned highway bridge girders, was 2050 kg/m^3. The density used for design calculations was 1970 kg/m^3, which represented the average density obtained during production. Test data from construction of a mid-rise building with lightweight concrete floors indicated an average compressive strength of 84 MPa with a theoretical plastic density of 1815 kg/m^3. Both lightweight concretes mentioned above were “sand lightweight” with most or all of the coarse aggregate consisting of STALITE lightweight aggregate. Work is underway to investigate the potential for using STALITE to make concrete with even higher compressive strengths.

The minimum equilibrium density of an “all lightweight” concrete made using STALITE is about 1600 kg/m^3. Design compressive strengths at this density can be at least 35 MPa.

4.2 Transfer and Development Length for Pretensioned Prestressing Strand

It has been demonstrated that equations in the AASHTO LRFD Specifications [4] for transfer and development lengths of pretensioned prestressing strands can be conservatively applied to members consisting of sand lightweight concrete [8].

4.3 Creep, Shrinkage, and Prestress Losses

Creep and shrinkage of lightweight concrete are generally assumed to be greater than values for comparable normal weight concrete. However, test results for creep and shrinkage for high strength lightweight concrete are similar to results for normal weight concrete [8,9]. In one comparison, a high-strength lightweight concrete mixture was shown to have less shrinkage compared to a similar normal weight concrete mixture, even though it had a significantly greater cementitious materials content [9]. Since research has also demonstrated that time-dependent prestress losses for lightweight concrete are similar to normal weight concrete, it has been concluded that current code expressions for estimating creep, shrinkage, and prestress losses may be used for lightweight concrete without modification [8].

4.4 Thermal Properties

The coefficient of thermal expansion for structural lightweight concrete is typically less than for normal weight concrete with the same compressive strength. Test data are available for a bridge deck concrete mixture using three types of lightweight aggregate, including STALITE [10]. Other thermal properties of STALITE lightweight concrete have been reported [11].

The reduced coefficient of thermal expansion of lightweight concrete combined with its reduced modulus of elasticity and shrinkage are expected to result in significantly reduced stresses, and therefore reduced cracking tendencies, in situations where concrete is placed in highly restrained conditions or where elevated concrete temperatures are expected, such as in mass concrete placements. Tests have demonstrated the reduced cracking potential for lightweight concrete deck mixtures [10].

4.5 Fatigue

Fatigue strength is not considered in bridge designs in the USA. However, tests to assess types of concrete for an offshore platform reported by Hoff [12], which included STALITE, showed good fatigue resistance.

4.6 Durability

Long-term durability is a critical concern for bridges and offshore structures. While durability of concrete structures depends on a wide range of factors, the two primary factors are permeability and the extent and severity of cracking. Compared to normal weight concrete with the same quality and compressive strength, the unique characteristics of lightweight concrete contribute to reduced permeability and significantly reduced tendency for cracking [9,13,14], thus leading to increased service life.

5. CONCLUSIONS

This paper has given a brief introduction to lightweight aggregates manufactured in the USA, and STALITE in particular. Several issues in the US design codes related to lightweight concrete were discussed. A few properties of lightweight concrete have also been presented. It is hoped that this discussion will serve to advance the exchange of information related to lightweight concrete between the USA and Europe.

REFERENCES

Cited references are listed below. Some of the cited references include lists of other references that may be of interest to the reader. Additional references are also available from the author that provide information on the use and performance of structural lightweight aggregate.

[1] Castrodale, R.W., Valum, R., Harmon, K.S.: "High-performance lightweight concrete bridges and buildings", Proceedings Eleventh High Performance Concrete (11th HPC) and Second Concrete Innovation Conference (2nd CIC), Tromsø, Norway. (2017)

[2] Castrodale, R.W., Zivkovic, J., Valum, R.: "Material properties of high performance structural lightweight concrete", Proceedings Eleventh High Performance Concrete (11th HPC) and Second Concrete Innovation Conference (2nd CIC), Tromsø, Norway. (2017)

[3] Castrodale, R.W.: "Expanded slate lightweight aggregate for high performance structural concrete," Proceedings *fib* Congress, Melbourne. (2018)

[4] American Association of State Highway and Transportation Officials (AASHTO). *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC. (2017)

[5] American Concrete Institute (ACI) Committee 318: "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," ACI, Farmington Hills, Michigan. (2014)

[6] EN-1992-1-1. "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings". CEN European Committee for Standardization, Brussels. (2004)

[7] Greene, G.G., Castrodale, R.W., Graybeal, B.A.: "Recent changes in *AASHTO LRFD Bridge Design Specifications* regarding lightweight concrete," Proceedings National Accelerated Bridge Construction Conference, Miami. (2015)

[8] Cousins, T., Roberts-Wollmann, C., Brown, M. "High-performance/high-strength lightweight concrete for bridge girders and decks," Report 733, National Cooperative Highway Research Program, Transportation Research Board, Washington. (2013)

[9] Chapman, D., Castrodale, R. "Sand lightweight concrete for prestressed concrete girders in three Washington State bridges," Proceedings, National Bridge Conference, Precast/Prestressed Concrete Institute, Chicago. (2016)

[10] Byard, B., Schindler, A.: "Cracking tendency of lightweight concrete," Highway Research Center, Auburn, Alabama. (2010)

[11] Cavalline, T., Castrodale, R., Freeman, C., Wall, J.: "Impact of lightweight aggregate on concrete thermal properties," ACI Materials Journal, 114(6), Nov.-Dec., pp. 945-956. (2017)

[12] Hoff, G.: "High strength lightweight aggregate concrete for arctic applications - Part 1: Unhardened concrete properties; Part 2: Mechanical properties; Part 3: Structural parameters," Special Publication 136, ACI, Farmington Hills, Michigan. (1993)

[13] Castrodale, R.W., Harmon, K.S.: "Durability of lightweight concrete bridges," Proceedings National Bridge Conference, Precast/Prestressed Concrete Institute, Chicago. (2008)

[14] Castrodale, R.W.: "Benefits of structural lightweight concrete … other than reduced density," Proceedings *fib* Congress, Melbourne. (2018)

SEMINAR LECTURES

Nordic mini-seminar: Structural lightweight aggregate concrete
Trondheim, Norway, February 20th, 2019

Production and Physical Properties of Expanded Slate Lightweight Aggregate

Jody R. Wall, PE
General Manager
Stalite Structural Lightweight Aggregate
Salisbury, North Carolina, USA
e-mail: jwall@stalite.com

ABSTRACT

This paper discusses the production of lightweight aggregate via the rotary kiln method and resulting material properties of expanded slate lightweight aggregate.

Key words: Lightweight aggregate, rotary kiln, material properties.

1. INTRODUCTION

The first investigation into the production of Expanded Shale Clay and Slate (ESCS) lightweight aggregates was undertaken in 1908. It was not until ten years later that the product found commercial application. The process of manufacturing an ESCS aggregate in a rotary kiln was patented by Stephen J. Hayde, a Kansas City ceramic engineer who recognized that clay brick that had excessive expansion could in fact, be utilized in the production of high quality lightweight aggregate for use in concrete products that had a significantly improved strength to weight ratio [1].

2. GEOLOGY

Stalite Lightweight Aggregate is produced using meta-argillite. This rock formed when quartz silt and sand particles mixed with volcanic ash from nearby erupting volcanoes as they settled to the bottom of the ocean floor. Once there, they became lithified into a solid rock. Later, intense heat and pressure metamorphosed the rock, giving it its foliation. Geologists have surmised that the meta-argillite formed on a volcanic arc that later collided with North America more than 450 million years ago. Silica is the predominant chemical component of meta-argillite. Alumina and iron oxides are also present in the material with minor constituents including titanium, manganese, and phosphorus.

3. MINING/QUARRYING

Selective mining is required when obtaining the slate required for the production of Stalite. The dip of the deposit, the angle at which the bed is inclined from the horizontal, in slates can be considerable. Faults with vertical offset of up to 10 meters are present in the quarry and occasional inter-mixed deposits of non-bloatable mudstone and diabase also present. Extensive testing and three dimensional modelling are used in the selective mining process to identify suitable bloatable materials.

4. MECHANISM OF EXPANSION

Slate and other materials which will bloat or expand must possess two qualities:

a) When it is heated to the point of incipient fusion, gases must be formed; the gases formed include carbon dioxide and sulphur dioxide. Calcite is the predominant source of carbon dioxide. Pyrite and marcasite are the sources of the sulphur dioxide.

b) The glass formed on heating the material must be of such a viscosity as to entrap the gases formed.

The triaxial diagram in Figure 1 is typically a good indicator of viscosity required for bloating of meta-argillitic slate and other materials used to produce lightweight aggregates [2].

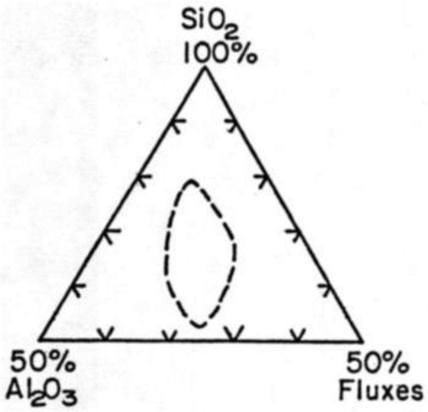


Figure 1 – Composition limits of bloating clays [2]

5. ROTARY KILN

The rotary kiln, in its simplest form, is a nearly horizontal refractory-lined cylinder, rotating about its longitudinal axis. The raw material is fed into the upper end and the heat is applied at the lower end, so the material travels counter-current to the heat flow. The material is heated in about 30 to 60 minutes, depending on the length, diameter, and rotational speed, to a maximum temperature of between 1050° and 1200° C. The heating rate is gradual for about 2/3 the length of the kiln, then it increases rapidly until the maximum is reached thus heating the interior of the particles so that gases that are liberated will be trapped by glass formed matrix [3].

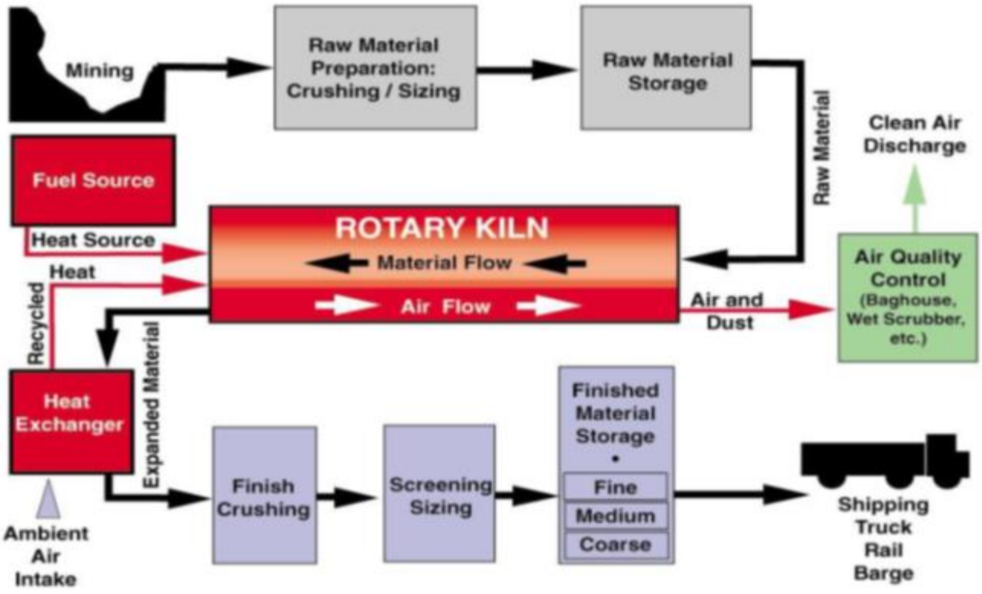


Figure 2 – Rotary kiln flow diagram [3]

The rotary kiln can be an inefficient heat exchanger if not managed properly. Only a small percentage of the heat applied can be used to bloat the material. The remainder of the heat can be lost through:

a) The combustion gases and moisture exhausting from the kiln
b) Radiation from the kiln shell
c) Retention in the aggregate discharged from the kiln

To minimize these thermal losses, we utilize a pre-heater to minimize the heat loss from the combustion gases exhausting the kiln. We also use insulation processes to minimize the heat radiation from the kiln and forced air coolers to recycle the heat from the discharged aggregate. The net result of these items is an efficient heat transfer system for the expansion of the raw materials.

6. PHYSICAL PROPERTIES

6.1 Absorption

Research has shown that the non-interconnected spherical pores in expanded slate lightweight aggregate do not completely fill when submerged in water [4]. Only the exterior pores and interior pores connected by micro cracks or fissures fill with water. In the research, the material was submerged in water containing florescent water-based dye for a period of six months. The material was removed from the water and the absorption percentage was determined. The absorption percentage of the materials averaged 8.0%. Samples were then dried and broken to reveal the interior pore structure. The exposed pore structure was viewed under a black light to determine penetration of the water and dye. The water and dye had only penetrated the exterior pores and interior pores connected by micro-cracks or fissures.

6.2 Specific Gravity vs Absorption

Results from specific gravity and absorption tests for Stalite shown in Table 1 are from material washed over a #4 screen and oven dried at the beginning of the test. The material was then submerged in water at 23°C for the durations shown. The original sample mass was large enough to allow for portions to be removed and tested for absorption and specific gravity while the remainder of the sample remained submerged. This allowed for continuous submersions as listed below. The specific gravity was tested by the pycnometer method as described in ACI 211.2 [5]. The absorption was tested after towel drying the aggregate as described in ASTM C127 [4].

6.3 Particle Strength

Lightweight aggregate particles cannot be tested in direct compression due to the manufactured nature of the aggregate. Normal density stone is tested in compression from cores of the competent rock being used. With the obvious inability to core lightweight rock and test in compression, the strength of the aggregate is best measured in terms of other tests that can be performed on the aggregate. The Los Angeles (LA) abrasion test (ASTM C131) is a measure of an aggregate’s strength and durability. Stalite has an LA abrasion loss of 25 to 28 percent which is very good. The compressive strength of the concrete made using expanded slate aggregate has regularly achieved over 70 MPa at 28 days. The early strengths of precast mixes have often achieved over 55 MPa in 2 days.

Table 1 – Specific Gravity vs. Absorption [4]

Submersion Time [H]	Specific Gravity ACI 211.2	Absorption ASTM C127 [%]
0	1.43	0.0
1	1.46	3.4
4	1.46	3.8
8	1.47	4.1
24	1.50	6.6
48	1.50	7.2
120	1.51	7.9
336	1.51	8.0

5. CONCLUSIONS

This paper gives a very general overview of the production of expanded slate lightweight aggregate and some general properties of the expanded materials. These properties are important in the production of lightweight concrete using expanded lightweight aggregates.

REFERENCES

Cited references are listed below. Additional references are also available from the author.

[1] Holm T.A. and Ries J.P., “Lightweight Concrete and Aggregates”, Chapter 46, *Significance of Test and Properties of Concrete and Concrete-Making Materials*, ASTM 169D, ASTM International, West Conshohocken. (2006)

[2] Riley C.M., “Relation of Chemical Properties to the Bloating of Clays,” *Journal of American Ceramic Society*, 30:4, 121-128. (2006)

[3] Holm, T.A. and Ries, J.P., “Chapter 2, Manufacturing of ESCS Lightweight Aggregates,” *ESCSI Reference Manual*, Expanded Shale, Clay and Slate Institute (ESCSI), Chicago. (2007)

[4] Wall, J. “ESCS Lightweight Aggregate Geotechnical Fill Properties and Applications,” Proceedings North Carolina GEO3T2 Conference, Raleigh. (2006)

[5] American Concrete Institute (ACI) Committee 211.2, Appendix B “Standard Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2),” ACI, Farmington Hills, Michigan. (1998)

Lightweight concrete for the E39 fjord-crossing project in Norway

Arianna Minoretti, Chief Engineer
State Department
Norwegian Public Road Administration
Trondheim, Norway
e-mail: arianna.minoretti@vegvesen.no

Simen Hellgren Holtberget, Overingeniør
Region Øst
Norwegian Public Road Administration
Oslo, Norway
e-mail: simen.hellgren.holtberget@vegvesen.no

Bernardo Costa, Overingeniør
Region West
Norwegian Public Road Administration
Stavanger, Norway
e-mail: bernardo.morais.da.costa@vegvesen.no

Johannes Veie, Chief Engineer
Region Øst
Norwegian Public Road Administration
Oslo, Norway
e-mail: johannes.veie@vegvesen.no

ABSTRACT

The Ferry free E39 fjord-crossing project in Norway is giving the opportunity to develop some new type of structures. The possibility to use lighter materials could, in some cases, optimize the structure in terms of response towards the environmental loads and in terms of cost. The different crossings and the related challenges are described in the paper.

Key words: Large concrete structures, marine environment, collisions, cracking

1. INTRODUCTION

During the recent years, the Norwegian Public Road Administration, with universities and consultants, has developed several feasibility studies for crossing the long and deep fjords along the E39. Submerged Floating Tube Bridges (SFTB) [1], Suspension Bridges on Tension Leg Platforms (TLP) or Floating Bridges could be an alternative to realize these challenging crossings. Every structure has different characteristics and specific needs that require a deep understanding of the structural behaviour of the bridge.

Generally, we can say that the possibility to use light materials will help in lowering the cost of the structures, but there are challenges related to the resistance of the structure towards, for example, impact loads that these structures in a marine environment have to face.

2 THE SUBMERGED FLOATING TUBE BRIDGE

The SFTB (Fig.1) is a submerged bridge, floating at a specific depth below the sea level. It has a closed cross section, similar to a tunnel, but it behaves like a bridge.

For long crossings, the structure needs some element to vertically stabilize it. These elements can be floating pontoons or tethers connecting the structure with the seabed. The tethers are the same elements used in the offshore structures.

Figure 1 – SFTB study for crossing the Sognefjord

In the design developed for the fjord crossing, the road is located in a twin tube bridge, where each tube allows a two lanes carriageway. The volume of the tubes is defined by the space needed for the road, the eventual pedestrian or bicycle path and the area for the variable ballast, that is activated in case of accidental situations.

Once the volume is defined, the buoyancy force that is uplifting the structure is also determined, being dependent from the weight of the volume of water displaced.

In the realized designs, the structure has been dimensioned to have a neutral buoyancy so that the vertical loads balance the uplifting force. Having a lighter structure would consequently mean that there will be the need to introduce a permanent ballast in the structure, while using a traditional concrete will allow to have some weight from the structural material to ballast the bridge.

Regarding the pontoons, the environmental forces they are exposed to depend also on their dimensions. This could lead to think that having a lighter pontoon would allow to reduce its dimensions and consequently to reduce the forces it is exposed to. But the waterline area of the pontoons is necessary to provide the required stiffness to avoid deformations during the quasi-static load conditions.

Having the same geometry, the possibility to use a lighter material could be nevertheless favourable for the dynamic behaviour of the structure. In fact, it is difficult to tune the response of the structure out from the dangerous resonance area of the environmental actions. A lighter and different material could therefore be an additional possibility for this such important task, due to the influence of the mass and of the material damping in the dynamic behaviour.

2 MULTI-SPAN SUSPENSION BRIDGE ON FLOATING FOUNDATIONS

The multi-span suspension bridge on floating foundations is a multi-span suspension bridge consisting of two rigidly land founded towers, and one or more floaters (floating towers). The floaters are based on Tension Legged Platform (TLP) technology, and thus give rotational stiffness about the horizontal axes, and reduced lateral deflection. The TLP foundations enables the concept to be founded on great depths. The tethers are connected to the floater, and anchored to the seabed with anchors.

The floaters can be built in different materials, where the main alternatives are separated as steel or concrete. In order to reduce forces in the structure a light buoyant material like LWA-concrete might be a desirable material. The desired dynamic behaviour of the structure will vary from fjord to fjord, and thus different materials needs to be considered. For the Bjørnafjord the northern land based tower was founded on a caisson. In order to reduce the forces due to wave loading LWA-concrete was necessary as the structure needed to be slimmed down. LWA-concrete was also used for the concrete floater alternative, where an aggregate of LC 50/55 was used for the design. In the further development of the multi-span suspension bridge on floating foundations LWA-concrete will be an important alternative for the concrete parts of the structure. Especially with regard to reducing the accumulation of hydrodynamic loads, but also when considering the balance between buoyancy and weight. Sensitivity studies will be a key factor when it comes to understanding the global behaviour of the concept, and LWA-concrete might be an important material to optimize the global behaviour of the structure.

With regard to construction the floaters and the caisson is suitable for LWA-concrete due to the fact that these are meant to be built in docks, and thus no pumping of concrete is required. For the elements where pumping is required (i.e. landbased pylons), normal concrete are considered.

3 FLOATING BRIDGE

The proposed floating bridge solutions to cross Bjørnafjorden, at the current stage, consist of roughly 5 km long steel box girders supported every 100m by steel columns on top of floating steel pontoons. The pictures above illustrate an end-anchored curved alternative without mooring lines as well as a side-anchored straight alternative with mooring lines.

Lightweight concrete (LC55) pontoons were chosen for the pontoons of both Bergsøysundbrua and Nordhordlandsbrua – two existing floating bridges in Norway. Lightweight concrete (LC45) pontoons were also considered for the floating bridges for Bjørnafjorden, where their self-weight would then contribute to approx. 2/3 of the total water displacement of the pontoon, with the remaining 1/3 coming from the girder.

The size, weight, impact resistance, construction process and maintenance requirements of the pontoons have a strong impact on the total cost, safety, and aesthetics. Keeping the pontoons at reasonable values of volume and weight is crucial to limit the hydrodynamic loads on the entire structure. Since changes in the weight of the pontoons will lead to changes in total buoyancy requirements and thus again in the pontoons' volume and weight, small pontoon changes can quickly lead to big overall changes. The ratio of resistance and flexibility of the cable stayed part of the bridge, to accommodate the permanent, traffic and environmental loads together with tidal variations, is an aspect to consider as well.

The strong sensitivity shown for these concepts makes them good candidates for the use of other materials, where lightweight concrete can definitely play a role.

Lightweight concrete in offshore structures

Kjell Tore Fosså, dr.ing
Kværner AS
Postal address: PO Box 74 ,
1325 Lysaker, Norway
e-mail: kjell.tore.fossa@kvaerner.com

ABSTRACT
Lightweight concrete is used in several offshore structures in order to reduce the overall weight. The concrete need to have a predicable durability, satisfy the minimum design requirements and easy to distribute and place in the form.

Key words: Lightweight concrete, large concrete structures.

1. INTRODUCTION

High performance lightweight concrete is used in several offshore structures in order to reduce the concrete weight. In general, the weight can be reduced with more than 20%. This can improve the cost and efficiency during the construction phase because more work can be performed on a barge or in dry dock before the structure is lifted/floated into a deep-water site or to location.
In addition, the buoyancy will be improved with less weight in the structure. And e.g. during tow-out phase, an improved buoyancy can be beneficial in order to have e.g. a better clearance to the seabed. For a concrete sub-structures that will float during operation (as Heidrun TLP), a lower weight of the concrete foundation will allow higher top-sides weight /2/.

2. OFFSHORE STRUCTURES CONSTRUCTED BY NORWEGIAN CONTRACTORS WITH LIGHTSEIGHT AGGREGATE

The following offshore structures were made with lightweight aggregate in the concrete is listed in Table 1. In this concrete, the course aggregate fraction was replaced partly/all with lightweight aggregate. LWA-concrete when all coarse aggregate was replaced by lightweight aggregate and MND-concrete (Modified Normal Density), when about half the volume of the coarse aggregate were replaced.

Table 1: Offshore structures with lightweight aggregate concrete

Project	**Type LWA**	**Density, kg/m3**	**Compressive strength grade (adapted to present standard)**	**Year complete**
Snorre foundation	Liapor 8	1950 *	LC55/60	1990
Heidrun TLP	Liapor 8	1950 *	LC55/60	1994
Troll A	Leca 800	2200 **	C61/75	1995
Hibernia GBS	Stalite	2200 **	C69/85	1997
Hebron GBS (only prequalified MND)	Stalite	2200 **	C71,5/88	2015
Pontoon for bridge				
Bergsøysund	Liapor	1920 *	LC50/55	1992

*LWA-concrete, **MND-concrete

Liapor 8 (expanded clay) was used as lightweight aggregate in the first projects in Table 1, but this were changed to Leca 800 for the MND concrete used in Troll A. For Liapor 8 and Leca 800 an optimized mixing process was used, where the concrete after complete mixing was remixed in separate drums before the concrete was distributed to the structure. Distribution was performed by crane and bucket or lift and conwayer belt. No pumping was performed as distribution method with LWA or MND concrete with Liapor 8 or Leca 800.

In the later projects, Stalite aggregate (expanded slate) has been used in MND concrete. This aggregate was saturated before mixing, and mixed as for normal density concrete. Distribution has normally been performed by pumping.

Picture of Heidrun in dry dock in Stavanger (1993), source Kværner

3 PROPERTIES

For all projects listed in Table 1, a considerable development program was executed to identify all relevant properties in the lightweight concretes. This was done to ensure that the selected composition satisfied the minimum requirements. Both the fresh concrete properties as well as the mechanical properties were thoroughly tested. The main challenge when using dry lightweight aggregate were absorption, but the good routines that were developed secured that the concrete quality was within the required tolerances.

The rebar density for offshore concrete structures is quit high and it is required that the concrete is robust, stable and have a high slump to ensure a good consolidation in the form.

During the concrete development for Heidrun TLP, the solution to improve both the workability and ensure a good stability was to use a special sand with higher filler content. This fine sand in combination with Liapor 8 gave a robust concrete.

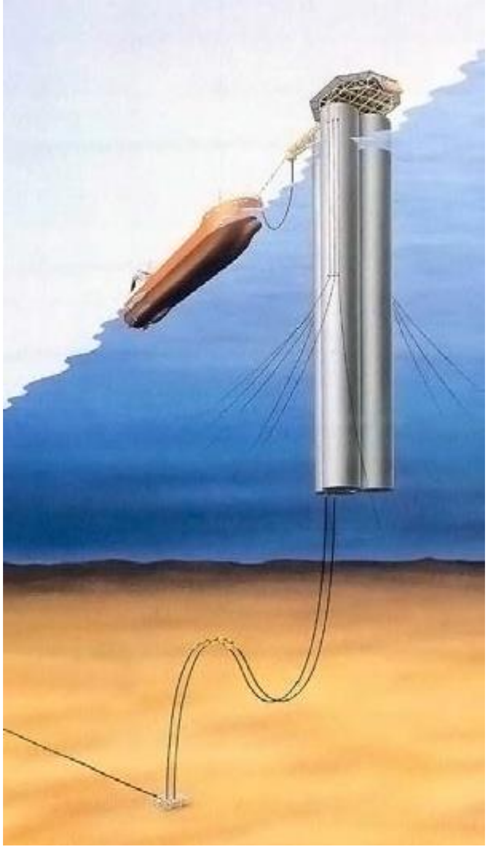
The durability properties for a concrete with lightweight aggregate is similar as for normal density concrete, but as always an adequate performance of the construction work was required together with a concrete cover thickness as designed. The compressive strength for lightweight aggregate concrete can be at similar level as for normal density concrete, but other mechanical properties such as e-modulus and fracture energy are normally reduced, and the reduction becomes more pronounced with higher content of LWA.

4 CONSTRUCTION METHOD

The most common construction method for vertical walls is slipforming for offshore structures. This is well suitable method both for lightweight concrete as well as normal density concrete. The concrete can be placed and vibrated in a similar manner as for normal concrete. Sometimes the vibrator frequency is slightly changed to ensure better response during vibration.

5 FUTURE CONCRETE CONCEPTS WITH LIGHTWEIGHT CONCRETE

There are in 2019 ongoing offshore project with lightweight concrete, which demonstrate that there are a marked for high performance concrete structure. As it listed in the Introduction Section, this is because the lightweight concrete in many instances is better with regard to cost and schedule. In the future, robust concretes will be selected that have a predicable durability, satisfy the minimum design requirements and are easy to distribute and place in the form. Pumpable concrete is preferred because this will release the cranes to other use. Improved logistics of rebar, concrete and materials will enable higher slipform speed, which can be beneficial for improved surfaces and quality of the finished concrete structure.



Picture of Spare Concept /3/ Tow to field /3/

REFERENCES

[2] Olsen, TO et.al, Concrete structures for oil and gas fields in hostile environments, Fib bulletin 50 (2009)
[3] Kværner – Concrete Solutions, Company presentation, Oslo (2013)

Nordic mini-seminar: Structural lightweight aggregate concrete
Trondheim, Norway, February 20th, 2019

Failure of lightweight aggregate concrete under compressive strain gradients

Jelena Zivkovic
M.Sc. PhD-candidate
Department of Structural Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: jelena.zivkovic@ntnu.no

Jan Arve Øverli
PhD, Professor
Department of Structural Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: jan.overli@ntnu.no

ABSTRACT

The use of lightweight aggregate concrete (LWAC) is limited as a mainstream construction material in structural applications. Partly this is related to the brittleness in compression compared to normal density concrete. Research done in the DACS-project has shown that high strength LWAC with Stalite as aggregate has much higher compressive strain levels than expected [1]. A strain gradient test, by loading prisms centrically and eccentrically, has been used to investigate strains and ductility in compression. The obtained strain level was much higher than expected.

Key words: Lightweight Aggregate Concrete, Testing in Compression, Strain level, Centric and Eccentric Loading, Strain Gradients

1. INTRODUCTION

This investigation is part of the ongoing research program “Durable advanced concrete structures (DaCS)”. The part of this program is to investigate structural behaviour of lightweight aggregate concretes (LWAC), concretes with an oven dry density below 2000 kg/m^3. The use of lightweight aggregate concrete (LWAC) is limited as a mainstream construction material in structural applications. A reason for that is related to the steepness of the descending branch of the stress-strain curve in compression [2]. Material models for compressive failure of concrete are normally based on a uniaxial compressive stress-strain curve obtained from tests, where the main assumption is uniform deformation of the concrete specimens. This assumption is reasonable for the ascending branch of the stress-strain curve, while for the descending branch is not realistic as it is always accompanied by significant lateral deformations. The lateral deformations are mainly caused by splitting cracks, which are formed and expand during the test. LWAC is characterized by more brittle post-peak material behaviour and uncontrolled crack propagation compared to normal density concrete (NWC).

In order to describe more in detail the compressive behaviour and to measure compressive strains, the effect of a strain gradient was introduced and varied in an experimental program. Strain gradients influences both the strength and the ductility [3]. Beam experiments tested in the DACS-project has shown that high strength LWAC with Stalite as aggregate obtained much higher compressive strain levels than expected [1]. The present experimental program included three batches of LWAC for the production of 21 prisms. The batches differed in using dry (0,10 % moisture content) or saturated (7,9 % moisture content) aggregate. The third batch included a small amount of polyvinyl alcohol fibres. Lightweight aggregate argillite slate, called Stalite, fraction size ½ inch, from North Carolina have been used. The geometry of the prisms were 100 x 140 x 480 mm (width x length x height). All samples were loaded centrically and eccentrically in compression. From the achieved experimental results it is visible that the lateral deformation of the most stressed fibre is counteracted by the less stressed fibres and that confine compressive stress. Close to the peak load the lateral deformations near the free surface become pronounced. Finally, in the post-peak region two different fractures developed and ultimate strains increased. In general larger eccentricity lead to increased strains (recorded strains in prisms test was in range from 3,08‰ and 6.82‰).

2. EXPERIMENTAL TEST PROGRAM AND RESULTS

The experimental program consist of 21 prisms, dimensions 100 x 140 x 480 mm (width x length x height), of plain LWAC which were loaded centrically and eccentrically in compression. This study looks at the differences of using dry-DLWAC (0,10 % moisture content) or saturated – WLWAC (7,9 % moisture content) aggregate, and the influence of adding 0.5% per cement mass of polyvinyl alcohol fibres – FLWAC, influence the compressive behaviour. Strain level at the concrete area were recorded with strain gauges (SG) and Linear Variable Differential Transformers (LVDT) at two sides of the prism. On the other two sides Digital Image Correlation (DIC) was used [4]. All the prisms were loaded in an electro-hydraulic, servo-controlled displacement machine with a capacity of 1000kN. Prisms were first preloaded with 100kN and later load was constantly applied with a loading rate of 0.3 mm/minute until failure. Average compressive strain levels recorded in all the prisms was between 3,08‰ and 6.82‰. In addition, for control of the material characteristics, compressive strength, tensile strength, E-modulus and fracture energy specimens were tested. To produce the concrete, a lightweight aggregate Stalite was used from the same batch to achieve an oven-dry density of about 1850 kg/m3 and a compressive cylinder strength of approximately 65 MPa. Test program and results are given in Table 1. Detailed test setup of the prisms is shown in Figure 1.

Table 1-Test program and results

Prism Nr.	Type of concrete	Aggreg. Moist. [%]	$f_{lc,cube}$ [MPa]	$f_{lc,prism}$ [MPa]	Eccentricity [mm]	P_{max} [kN]	P_{calc} [kN]	$\varepsilon_{c,LVDT}$ [‰]	$\varepsilon_{c,DIC}$ [‰]
1-3	DLWAC	0.1	77.9	57.5	e=0	804	763	2.69	3.12
4-6					e=7.77	668	513	2.51	3.47
7-9					e=23.33	495	382	2.70	3.81
1-3	WLWAC	7.9	80.7	53.5	e=0	746	791	2.59	3.40
4-6					e=7.77	648	531	2.19	3.69
7-9					e=23.33	541	395	2.96	4.53
1	FLWAC	7.9	77.6	46.7	e=0	653	760	2.46	2.94
2					e=7.77	669.9	511	2.18	4.54
3					e=23.33	577.8	380	3.38	6.82

Where $f_{lc,cube}$ is compressive cube strength; $f_{lc,prism}$ is compressive prism strength (P_{max} divided with prism cross cestion 100x140mm) ; P_{max} – load level of maximum load; P_{calc} – hand calculation of maximum load; $\varepsilon_{c,LVDT}$ – maximum concrete compressive strain recorded with LVDT; $\varepsilon_{c,DIC}$ – maximum concrete compressive strain recorded with DIC;

(a) *(b)* *(c)*

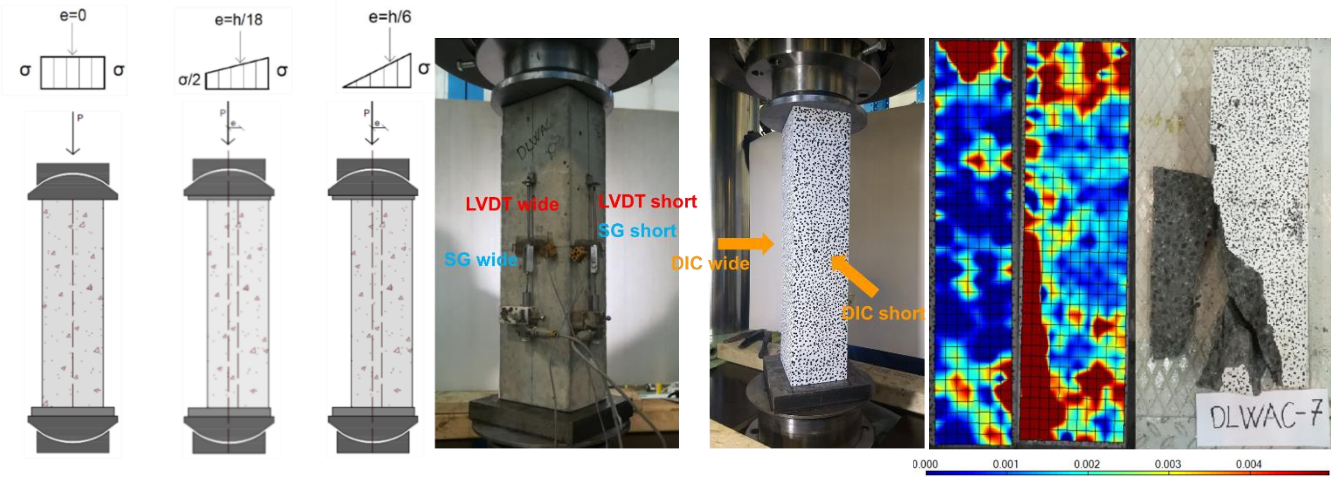


Figure 1 – (a) Detailed test setup of prisms with loading conditions; (b) setup of measuring devices at all four sides; (c) detailed strain field recorded with DIC just before failure and failure of prism

3. DISCUSSION AND CONCLUSIONS

This study investigates at the differences using dry or saturated aggegatee, and the effect of polyvinyl alcohol fibres on the compressive behaviour of LWAC. Crack propagation depended on the loading conditions. Prisms subjected to centrically loading experienced large cracks and the lowest ultimate compressive strain., while prisms loaded eccentrically only cracked at the most stressed part with higher strains. By using DIC, detailed strain fields of the observed compressive zones have been recorded, see Figure 1(c). In general, measuring devices were in a good agreement, but close to failure larger strains and localization were measured using DIC, compared to the strain values measured with the SGs and LVDTs. The concrete with the water saturated aggregate had somewhat higher strains and ductility than the concrete with dry aggregate. Through qualitative visual inspection of the fracture, it was observed that the concrete with the saturated aggregate had the most explosive fractures. By introducing a small amount of fibres (0,5% of the cement mass) the concrete became significantly more ductile, with a maximum compressive strain of 6,82 ‰, and the fracture was not explosive. Eurocode 2 [5] does not differ between lightweight concrete with different types of aggregates, and underestimated the largest strains in this experiment by 75-88 %.

The experimental setup of the prisms and the eccentricities were the same as in an earlier experiment and are therefore comparable [3]. The earlier studies looked at the lightweight concrete Liapor 8 and different types of normal weight concrete. Table 2 compare new and old experiments. A ductility index D is calculated as:

$$D = \frac{\varepsilon_{cu} - \varepsilon_{el}}{\varepsilon_{el}} \cdot 100\% \qquad (1)$$

where ε_{cu} is maximum compressive strain and ε_{el} is strain corresponding to elastic state. It is clear that LWAC with Stalite showed more ductile behaviour compared with LWAC with Liapor 8. Compared to normal density concretes the ductility is very similar while registered strains are much higher. When adding just small amount of polyvinyl alcohol fibres the ductility is doubled.

Table 2 - Comparison with experimental work from 1993 [2]

Type of concrete	Eccentricity [mm]	$f_{lc,prism}$ [MPa]	$f_{lc,cube}$ [MPa]	ε_{cu} [‰]	$D_{,LVDT}$ [%]	$D_{,DIC}$ [%]
DLWAC	e=0	57.5	77.9	3.12	11.2	13.3
	e=7.77			3.47		
	e=23.33			3.81		
WLWAC	e=0	53.5	80.7	3.40	15.1	14.9
	e=7.77			3.69		
	e=23.33			4.53		
FLWAC	e=0	46.7	77.6	2.94	37.2	37.6
	e=7.77			4.54		
	e=23.33			6.82		
Liapor 8	e=0	86.8	93.8	3.12	9.6	
	e=7.77			3.41		
	e=23.33			3.55		
Gneis/ Granitt	e=0	81.4	104.1	2.61	14.5	
	e=7.77			2.97		
	e=23.33			3.16		
Basalt	e=0	89.0	105.1	2.72	31.7	
	e=7.77			3.31		
	e=23.33			3.45		
Kvartsitt	e=0	86.5	106.7	2.47	14.8	
	e=7.77			2.81		
	e=23.33			2.84		

Where $f_{lc,prism}$ is compressive prism strength; $f_{lc,cube}$ is compressive cube strength; ε_{cu} – maximum concrete compressive strain ; $D_{,LVDT}$ – ductility index calculated from maximum concrete compressive strain recorded with LVDT; $D_{,DIC}$ – ductility index calculated from maximum concrete compressive strain recorded with DIC;

Acknowledgment

The work presented in this paper is part of ongoing PhD study in scope of the DACS project (Durable Advanced Concrete Solutions). The DACS partners are Kværner AS (project owner), Norwegian Research Council, Axion AS (Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens vegvesen), Norwegian University of Science and Technology (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS. Jelena Zivkovic would like to express hers outmost gratitude to the supervisors and all the project partners for contributions and making this PhD study possible. J. Zivkovic would like to thank to Master students Aleksander Hammer and Håvard Lauvsland for the help during experimental work.

REFERENCES

[1] Zivkovic, J. and Øverli, J.A.: “Ultimate compressive strain in lightweight aggregate concrete beams”, *fib PhD* Symposium in Prague, pp. 829–836, (2018).

[2] EuroLightCon. “Lwac Material Properties”. Document BE96-3942/R2, December 1998.

[3] G. Markeset.: “Failure of concrete under compressive strain gradients”. PhD diss., Norwegian Institute of Technology, University of Trondheim, Norway. (1993)

[4] N. McCormick and J. Lord.: “ Digital Image Correlation for Structural Measurements”. ICE institution. Civil Engineering, 165 (CE4), pp. 185–190 (2012).

[5] EN 1992-1-1 (2004), “Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings”.

Effect of loading rate on the fracture energy of lightweight aggregate concrete subjected to three-point bending test

Jelena Zivkovic
M.Sc. PhD-candidate
Department of Structural Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: jelena.zivkovic@ntnu.no

Seyed Mohammad Javad Razavi
M.Sc. PhD-candidate
Department of Mechanical and Industrial Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: javad.razavi@ntnu.no

Filippo Berto
PhD, Professor
Department of Mechanical and Industrial Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: filippo.berto@ntnu.no

Jan Arve Øverli
PhD, Professor
Department of Structural Engineering
Faculty of Engineering Science
Norwegian University of Science and Technology
N-7491 Trondheim, Norway
e-mail: jan.overli@ntnu.no

ABSTRACT

This study investigates the effect of loading rate on the fracture energy of lightweight aggregate concrete (LWAC) in the laboratory using three-point bending test. In addition, the effect of aggregate moisture and water/cement ratio on loading rate sensitivity was followed. Results show that increasing the loading rate leads to enhancement of the load-bearing capacity and fracture energy of the concrete. These results are promising having in mind that LWAC and especially high strength LWAC have brittle nature and fast crack/fracture development.

Keywords: Lightweight Aggregate Concrete, Three-point bending, Fracture energy, Loading rate

1. INTRODUCTION

This investigation is part of the ongoing research program "Durable advanced concrete structures (DaCS)". The part of this program is to investigate structural behaviour of lightweight aggregate concretes (LWAC), concretes with an oven dry density below 2000 kg/m^3 [1]. One of the main problem considering the use of LWAC is brittleness followed with fast crack/fracture development. In order to test behaviour of LWAC under different loading rates special experimental program was created. Three sets of test specimens were produced using lightweight aggregate argillite slate from North Carolina, called Stalite, fraction size ½ inch, from the same batch, where the water content in aggregate varied by 0.1%, 7,9% and 12.5%. From each concrete, 16 small beams and small samples (i.e. cubes and cylinders) were produced. The geometry of the beams was 50 × 50 × 550 mm (width × height × length). All samples were pre-notched and loaded under three-point bending. The loading rate was varied from 0.1 mm/min to 100 mm/min.

2. EXPERIMENTAL TEST PROGRAM AND RESULTS

The experimental program consist of 48 small beams, dimensions 50 × 50 × 550 mm (width × height × length). Beams were produced from three different lightweight aggregate concretes marked as dry-DLWAC (contain lightweight aggregate (LWA) with 0.10% moisture content) and saturated one marked as WLWAC-1 (LWA with 7.9% moisture content) and WLWAC-2 (LWA with 12.5% moisture content). Concrete recipes are given in Table 1.

Table 1 – Concrete mixture for DLWAC, WLWAC-1 and WLWAC-2

Constituent	DLWAC Weight [kg/m^3]	WLWAC-1 Weight [kg/m^3]	WLWAC-2 Weight [kg/m^3]
Moisture of the aggregate [%]	0.1	7.9	12.5
Water/cement ratio [w/c]	0.32	0.33	0.37
Cement (Norcem Anlegg FA)	442.2	440.3	427.5
Silica fume (Elkem Microsilica)	23.3	23.2	22.5
Water (free)	146	180.8	203.7
Absorbet water Stalite+sand (24 hours)	6.1	38.8	47.2
Sand (Ramlo) 0-2 mm)	230	231	229.4
Sand (Årdal (NSBR) 0-8 mm)	536.8	539	535.5
Aggregate (Stalite 1/2")	515.4	517.5	514
Superplasticiser (Mapei Dynamon SR-N)	3.3	3.9	3.1

Prior to the fracture tests, a set of cylindrical specimens were tested for each type of concrete using compressive and tensile tests to obtain the compressive and tensile strengths of the studied concretes. According to the test results, the compressive strengths were 82 MPa (DLWAC), and 84.8MPa (WLWAC-1) and 74.6MPa (WLWAC-2) and tensile strengths were 4.72 MPa (DLWAC), 4.86MPa (WLWAC-1) and 4.09MPa (WLWAC-2).

All the prisms were loaded under three point bending with an electro-hydraulic, servo-controlled displacement machine with a capacity of 100kN (see Figure 1). Testing span was 500 mm and beams were pre-notched in middle span, with notch length of 20 mm. Load was constantly applied with four different loading rates of 0.1, 1, 10 and 100 mm/min until failure. The applied load and the corresponding displacement in the middle span were recorded with the load cell during the whole test.

3. DISCUSSION AND CONCLUSIONS

The loading rate dependency of the fracture energy in three different lightweight concretes namely DLWAC, WLWAC-1 and WLWAC-2 with different moisture levels of lightweight aggregates has been investigated in this research. The representative load-displacement plots of the tested concrete specimens are illustrated in Figure 2.

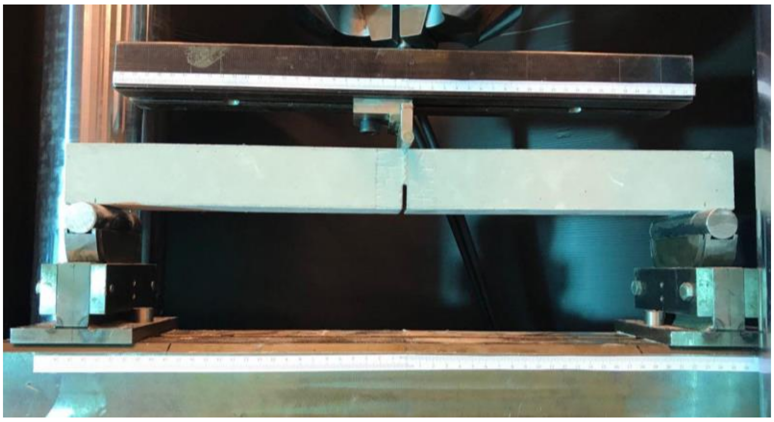


Figure 1 – Three-point bending test configuration.

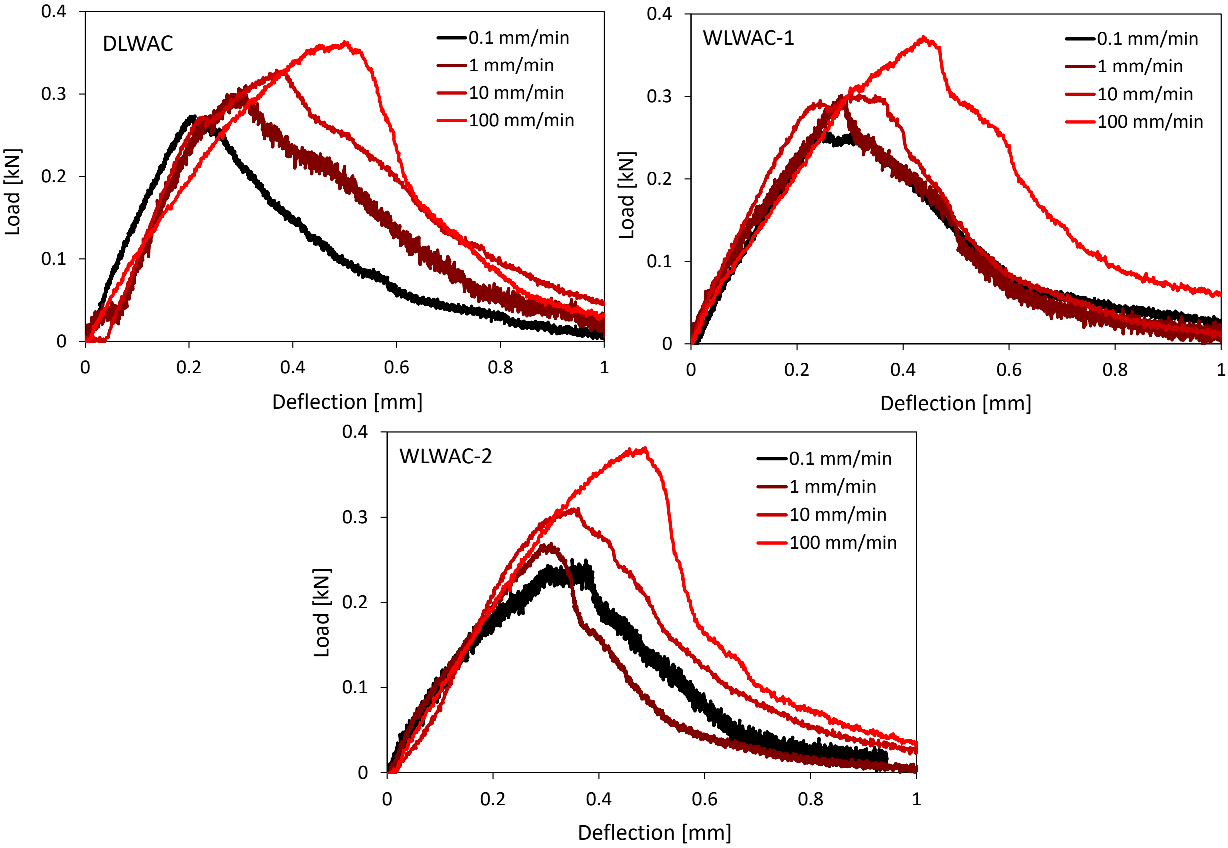


Fig. 2. Representative load-displacement response of the tested pre-cracked concrete specimens under three-point bending.

All the prisms showed ductile behaviour, after peak load was reached load slightly fail down until final failure happened. Through qualitative visual inspection of the fracture, it was observed that the concrete with the saturated aggregate (i.e. WLWAC-2) had the most explosive fractures. These results are of special interest having in mind that here was tested high strength LWAC, compressive strength above 60 MPa [1].

The fracture energies of the tested concretes were then calculated using the standard procedure proposed by SINTEF [2] and the results are given in Fig. 3. According to the SINTEF standard for fracture testing, the fracture energy G_f was calculated as:

$$G_f = \frac{W_o + 2 \cdot 0{,}4 \cdot p \cdot 9.81 \cdot \delta}{b \cdot h} \left[\frac{Nm}{m^2}\right] \qquad (1)$$

where W_o is positive area under load-displacement graph, and p is weight of the concrete samples, δ is maximum recorded dilatation and b, h are measured width and height of fracture area.

According to Figure 2, increasing the loading rate results in higher peak load values in all three different concrete specimens, having 28%, 21% and 41% higher peak load values under 100 mm/min loading rates compared to 0.1 mm/min loading rate for DLWAC, WLWAC-1 and WLWAC-2, respectively. The same trend of improvement was observed dealing with the fracture energies of the tested specimens (see Figure 3).

Although fracture energy of the tested DLWAC, WLWAC-1 and WLWAC-2 specimens under standard static loading rate of 0.1 mm/min [2] was 87.6, 93.8 and 72.1Nm/m^2, however, increasing the loading rate up to 100 mm/min increased these values to 136, 128.2 and 125.8 Nm/m^2 having and enhancement of 55%, 36% and 74%, respectively. According to the test results, increasing the loading rate from 0.1 mm/min to 1 mm/min resulted in enhancement of the fracture energies, however, only limited changes were observed when the loading rate was increased from 1 mm/min to 10 mm/min. In general, the lowest and the highest fracture energy values were obtained for the case that the specimens were tested under 0.1 mm/min and 100 mm/min.

The concrete with the low water saturated aggregate (i.e. WLWAC-1) had somewhat lower loading rate sensitivity than the concrete with dry aggregate. This can be related to the lower ductility of the mentioned concrete compared to DLWAC. On the other hand, increasing the moisture of the aggregate to a higher level in WLWAC-2 results in higher water to cement ratio leading to lower strength of the concrete making it the most loading rate sensitive concrete in this study.

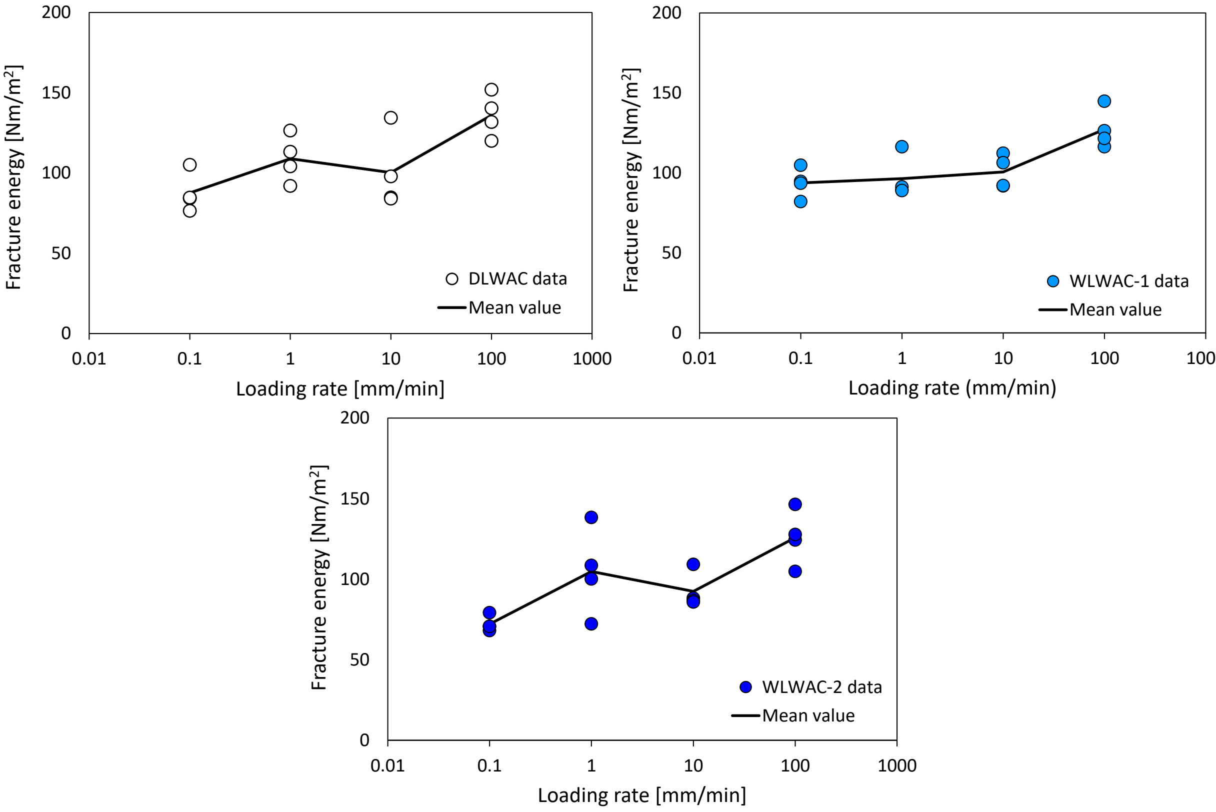


Fig. 3. Fracture energy versus loading rate for the tested pre-cracked concrete specimens under three-point bending.

Acknowledgment

The work presented in this paper is part of ongoing PhD study in scope of the DACS project (Durable Advanced Concrete Solutions). The DACS partners are Kværner AS (project owner), Norwegian Research Council, Axion AS (Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens vegvesen), Norwegian University of Science and Technology (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS.

REFERENCES

[1] EuroLightCon. "Lwac Material Properties". Document BE96-3942/R2, December 1998.
[2] SINTEF procedure KS14-05-04123.

ISBN: 978-82-8208-066-8 ISSN 0800-6377

A list of previous and upcoming Nordic workshops is available on www.nordicconcrete.net

Printed (made) by: NTNU Grafisk senter