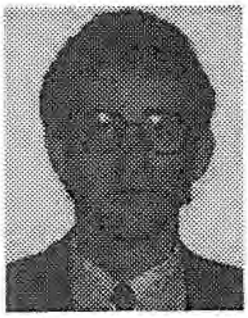
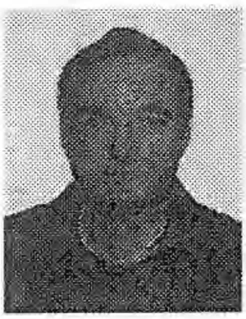
PRECAST SANDWICH ELEMENTS OF LIGHTWEIGHT AGGREGATE CONCRETE





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ABSTRACT: The paper describes the production and documentation of precast elements of Lightweight Aggregate Concrete (LWAC) with an open structure. The LWAC produced is a no-slump, roller compacted concrete, with dry densities (ρ) in the range 500-1800kg/m^3 and compressive strengths (f_c) of 2-30 MPa in most elements, which are used as walls or as roof and floor slabs. The two alternative documentation procedures "Design by Testing" and "Design by Calculation" are discussed. The formulas in the CEN-standard from TC177 for bending tensile strength and element shear strength are verified by comparation with the experimental results.

KEYWORDS: Lightweight aggregate concrete, shear strength, prefabricated, european standardisation

1. INTRODUCTION

Prefabricated concrete elements are used in numerous structures in Northern Europe due to their price/quality competitiveness compared to the in-situ cast concrete. These elements are produced with normal weight concrete, aerated autoclaved concrete or Lightweight Aggregate Concrete with open or closed structure. A combination of those concretes can be used for special applications or conditions.

The precast elements of Lightweight Aggregate Concrete (LWAC) with an open structure have been used for more than 40 years in Europe and has a large market share (over 50% in Denmark, 10% in Germany). The precast elements are used as walls or as roof and floor slabs. The slabs are produced with homogeneous, hollow-core or multi layered sandwich cross-sections as shown in Figure 1, whereas the walls usually have a homogeneous cross-section.

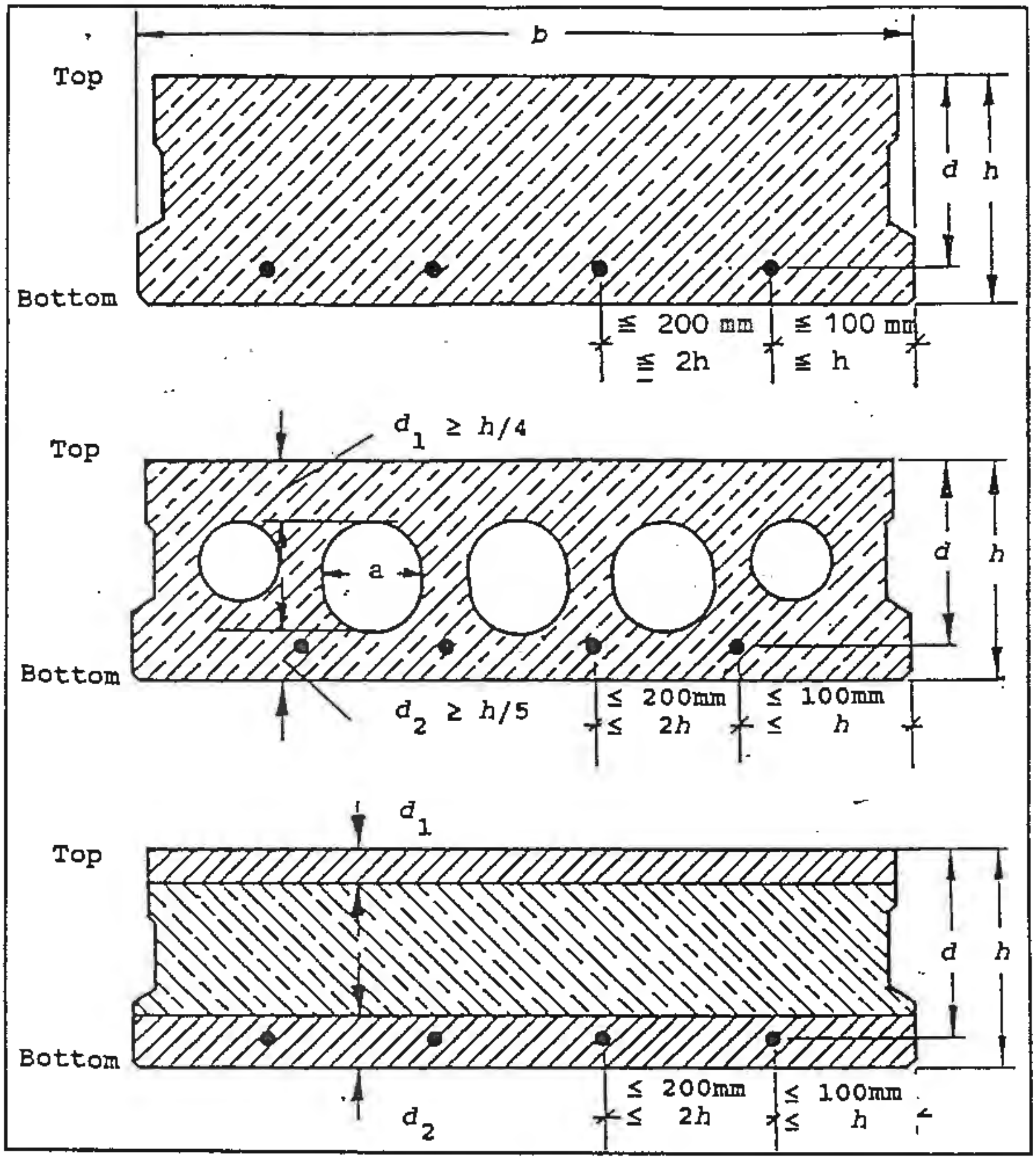

Figure 1. Types of cross-sections.

This paper describes the production and design of prefabricated sandwich floor and roof elements of (LWAC). The LWAC is produced as a no-slump, roller compacted concrete, with dry densities (ρ) in the range 500-1800kg/m^3 and compressive cylinder strengths (f_c) of 2-30 MPa in most elements.

The elements span length (L) is up to 7-8m, width (b) up to 1.2m in slabs, and thicknesses from 100mm to 300mm, (although other dimensions can be produced).

The concrete mix and the production method leads to simple formwork, low cement consumption, low weight and increased heat insulation. These advantages will usually result in lower production, transportation, erection and isolation costs than in situ cast concretes, a fact which in combination with the improved quality have lead to a large market share.

2. PRODUCTION OF LWAC ELEMENTS

The LWAC is placed in the form in one or several layers (Figure 2). The surface of each layer is adjusted with a plough (Figure 3) after positioning the reinforcement. The LWAC is compacted in the form by a roller (Figure 4) or a plate vibrator, which may be combined with vibration of the casting form. The element is finally steam cured for 8 to 16 hours before the removal of the form.

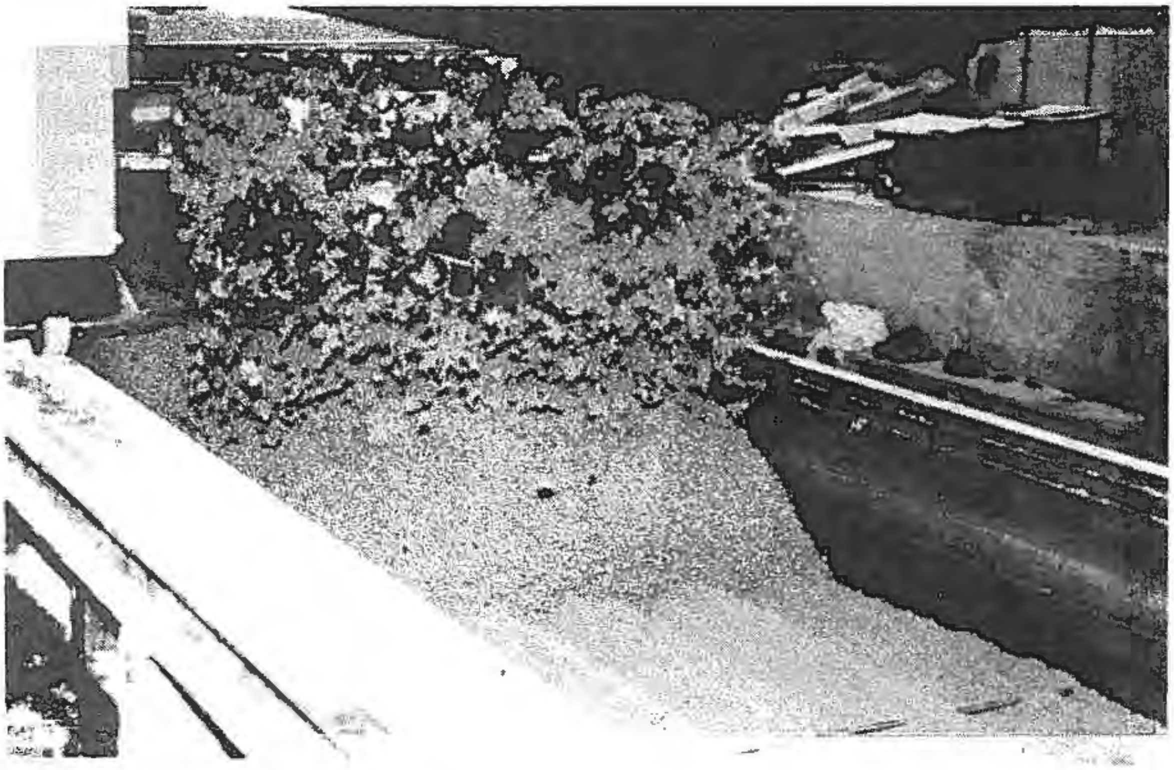

Figure 2. Placing the concrete in the form

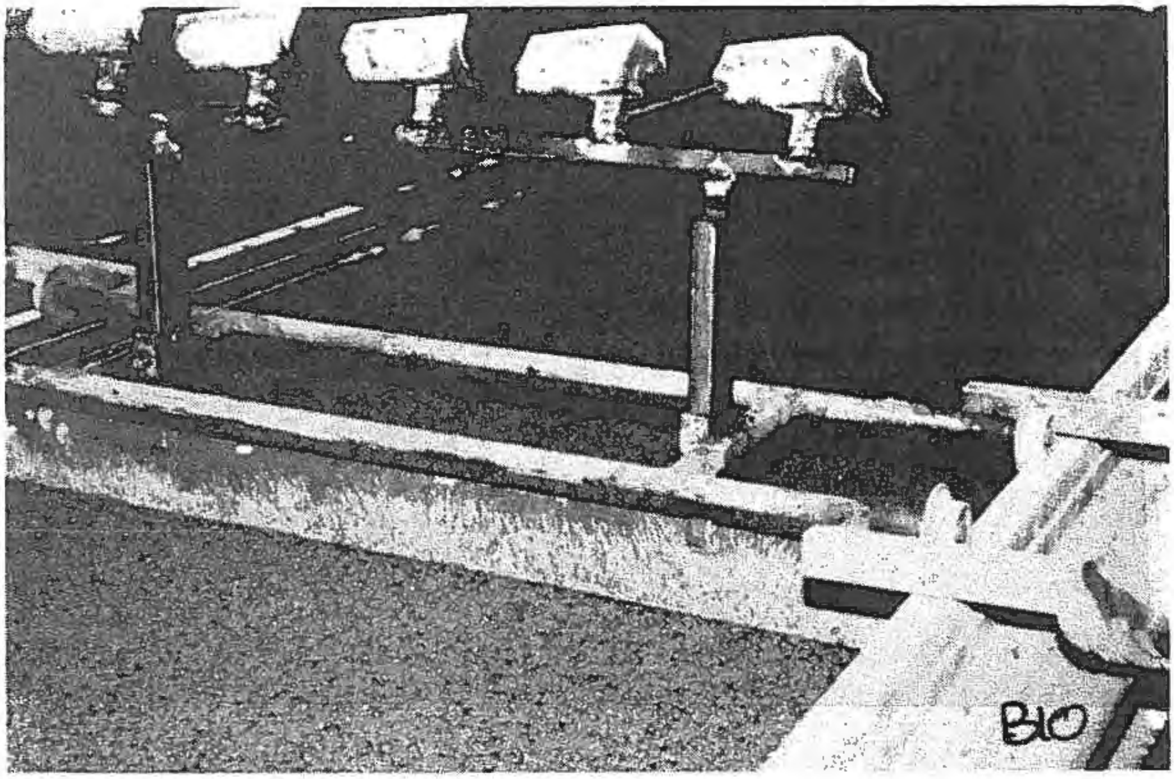

Figure 3. Adjusting the layer and ensuring that the reinforcement is embedded in the bottom layer.

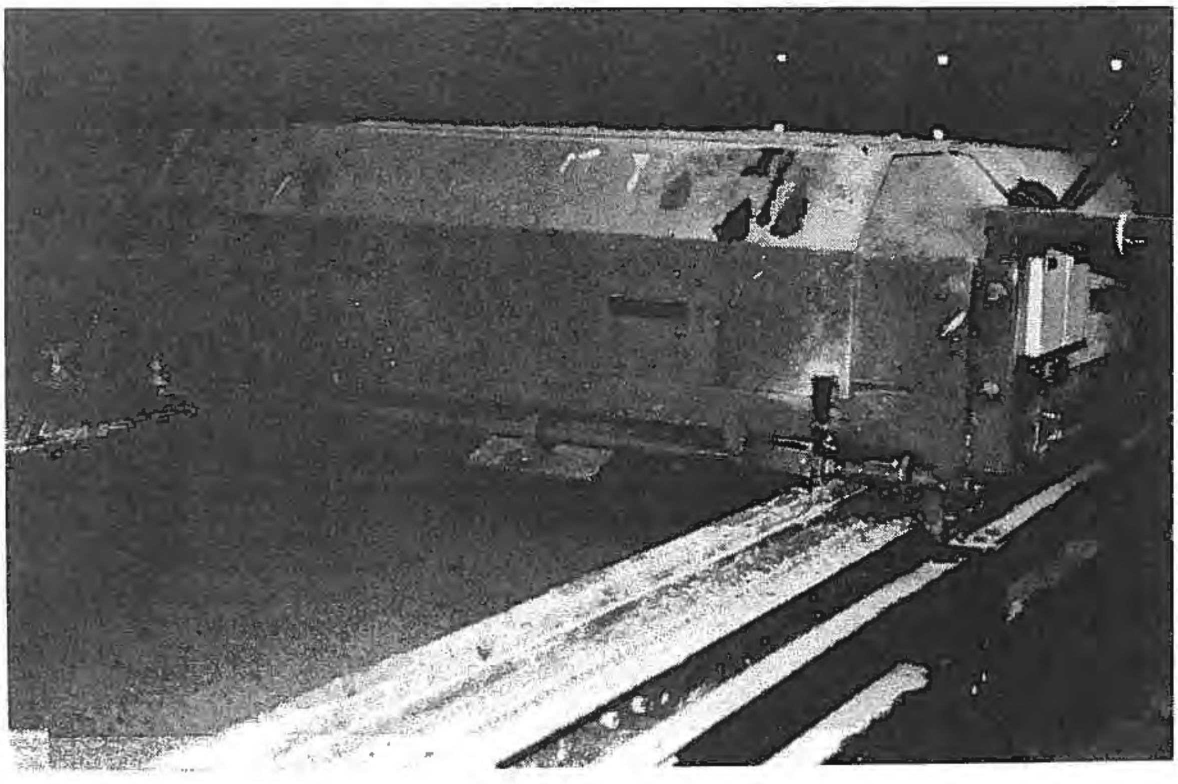

Figure 4. Roller compacting of the concrete.

The concrete mix and the roller compaction leads to a concrete with a more or less open structure depending on the mix design and the water content. The structure can be inspected by thin-section microscopy as shown in Figure 5 and 6.

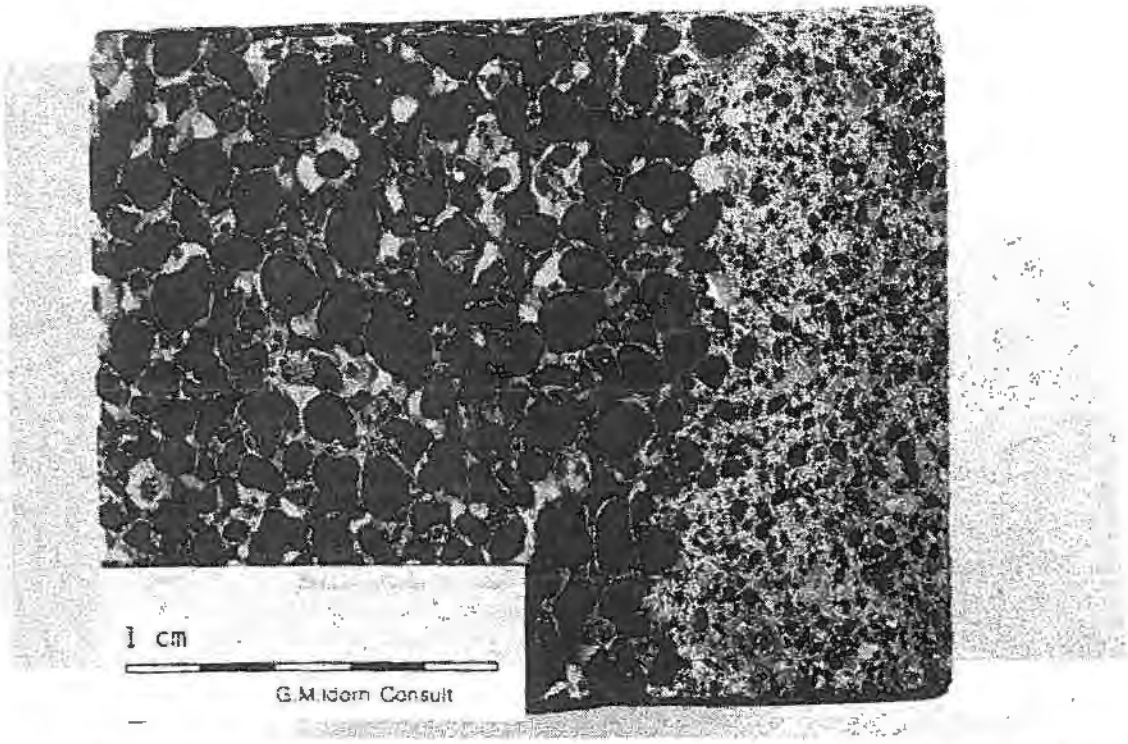

Figure 5. Cross section of element with top layer (density 1600kg/m^3) center and middle layer (density 550kg/m^3).

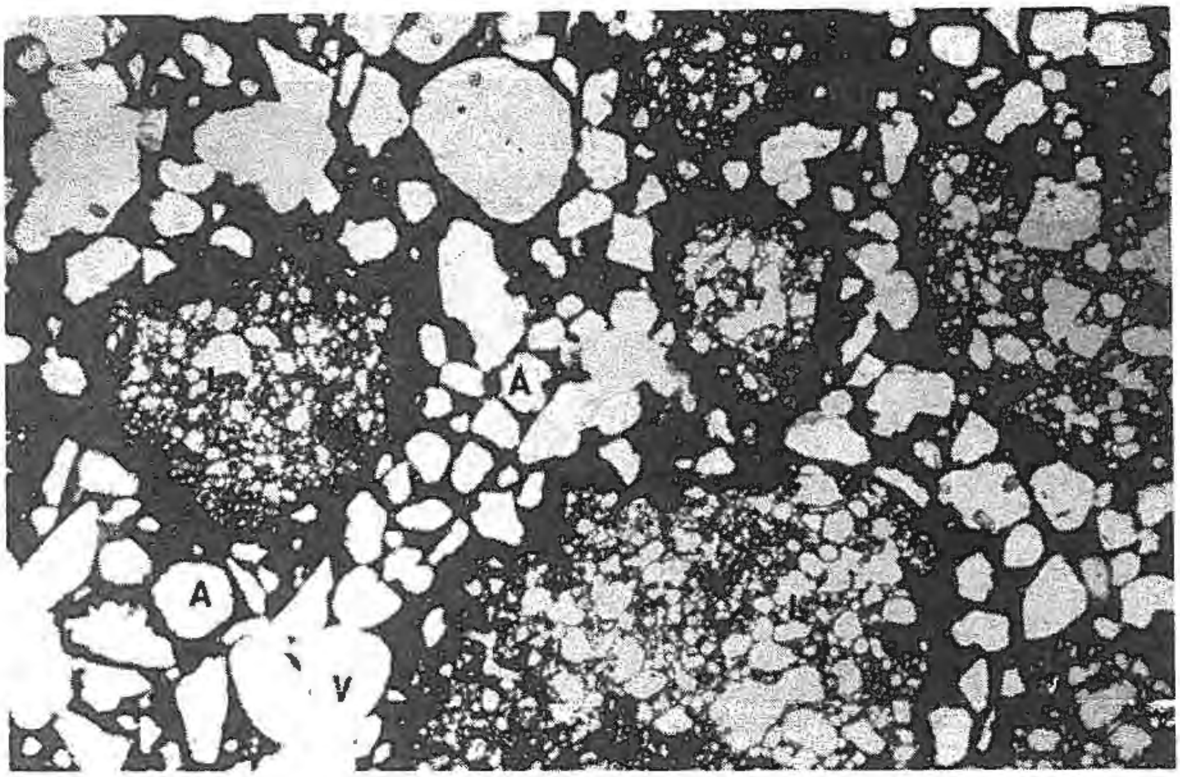

Figure 6. Thin section image of concrete with density 1600kg/m^3 (Top layer). V indicates Air Void, A aggregate and L lightweight aggregate.

The mix design, placing and compaction procedures lead to moderate variations in the dry densities and strengths. The load-carrying capacity of the element does, however, show a much lower variation (the shear strength of identical components cast the same day will usually vary 5%, which is far less than in in situ cast concrete).

3. CORROSION PROTECTION

The elements are used in the passive and moderate environments where they will not be exposed to chlorides or sulphates, nor to the combination of freezing and water (since the aggregates and the open concrete can be damaged by freezing). These environments cover most of the concrete used in Europe and requires only a fairly simple corrosion protection.

The reinforcement is usually coated with a simple cement-latex coating, which gives a sufficient corrosion protection in those mild environments. This corrosion protection is much simpler than what is usually required [1] in normal weight concrete with a closed structure, but has been used successfully in numerous LWAC-elements during the last 40 years, just as a similar approach has been used with equal success for even more decades on reinforcement and steel beams embedded in masonry .

4. DESIGN BY TESTING

The load carrying capacity, stiffness and other element properties can be documented by calculation using static formulas and material parameters or by full-scale testing.

The "Design by Testing" is thus an alternative to the more common "Design by Calculation", but is somewhat more expensive. The cost is, however, often justified, since the available formulas may be overly conservative and lead to expensive products and structures. The full-scale tests give a better documentation and enable a higher declaration of capacity and stiffness. The testing costs have, however, lead a number of countries to combine a few yearly full-scale tests with static calculations and material tests on LWAC specimens, thus reducing the testing costs and still obtaining a fairly correct documentation.

Full-scale testing has for some years been used in Denmark, based on a number of standardized test methods ([12],[13],[14]) valid in the 5 Nordic countries: Denmark, Norway, Sweden, Finland and Iceland. These methods are similar to those being developed by CEN/TC177.

Depending on the size of the production the full-scale tests are carried out 4-8 times monthly by each producer in a permanent testing bench (Figure 7) at the factory. The test results are evaluated with simple static rules, leading to a few parameters which are treated statistically.

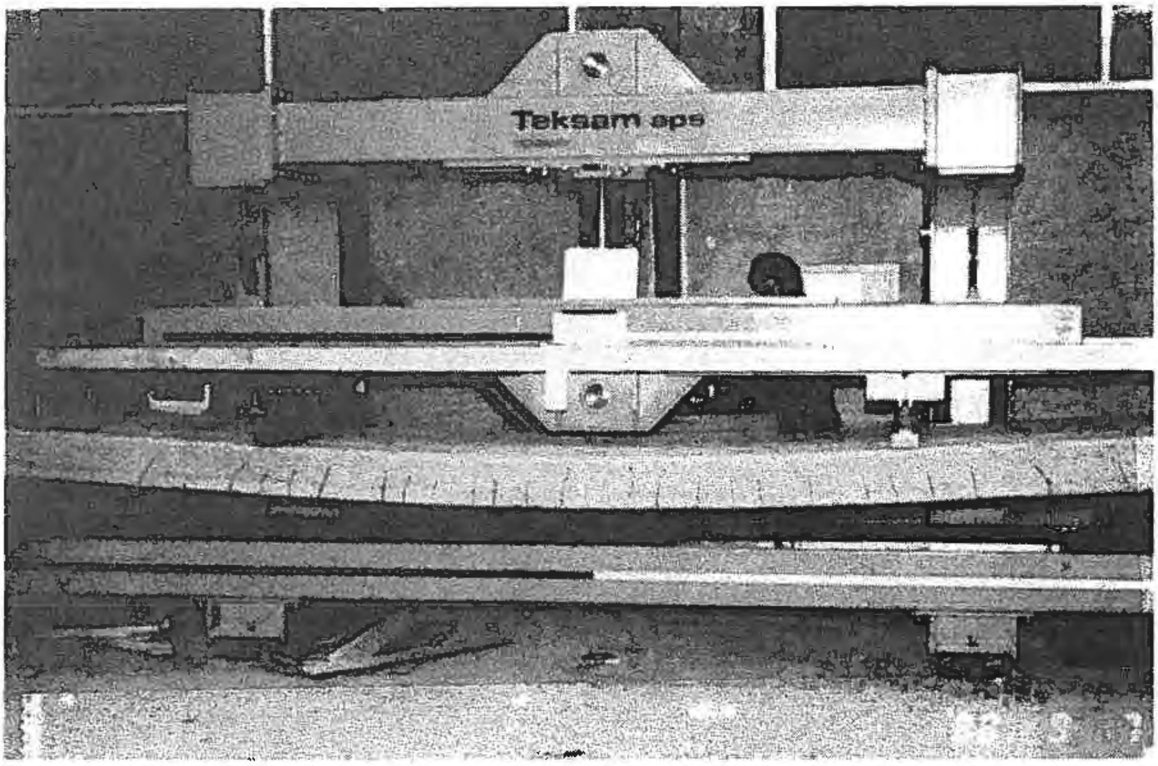

Figure 7. Full scale testing of floor slab.

The bench is controlled and calibrated by a third party inspection, just as the testing staff, the sampling, the results and the interpolations are controlled by the third party.
The types of failure are recorded and will - for the current designs - be either bending failure or shear failure. The bending failure is usually ductile and preceded by a well-developed crack pattern as shown in Figure 7. The shear failure is more brittle, but will be preceded by shear cracks starting from the middle layer as seen in Figure 8.

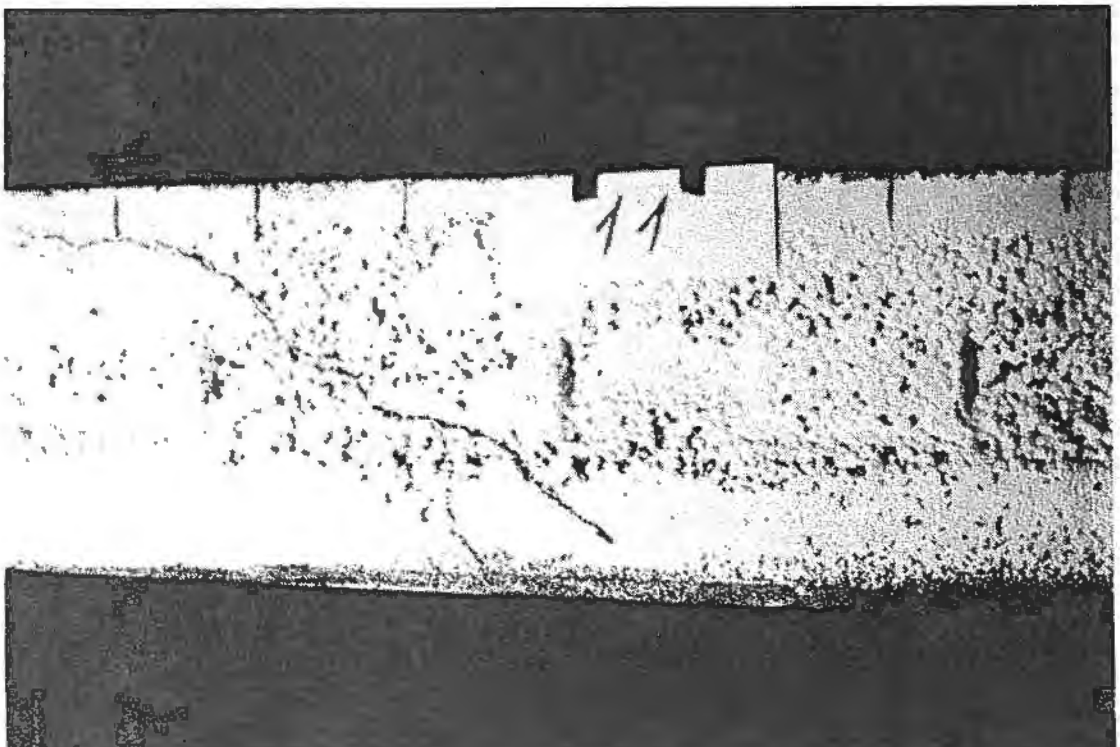

Figure 8. Initiation of shear crack.

The load increase from the initiation of the shear crack to the shear failure is small (in contrast the load increase from initial bending crack to bending failure) so loading steps must be fairly small to observe the crack propagation which ends in a typical shear failure as shown in Figure 9.

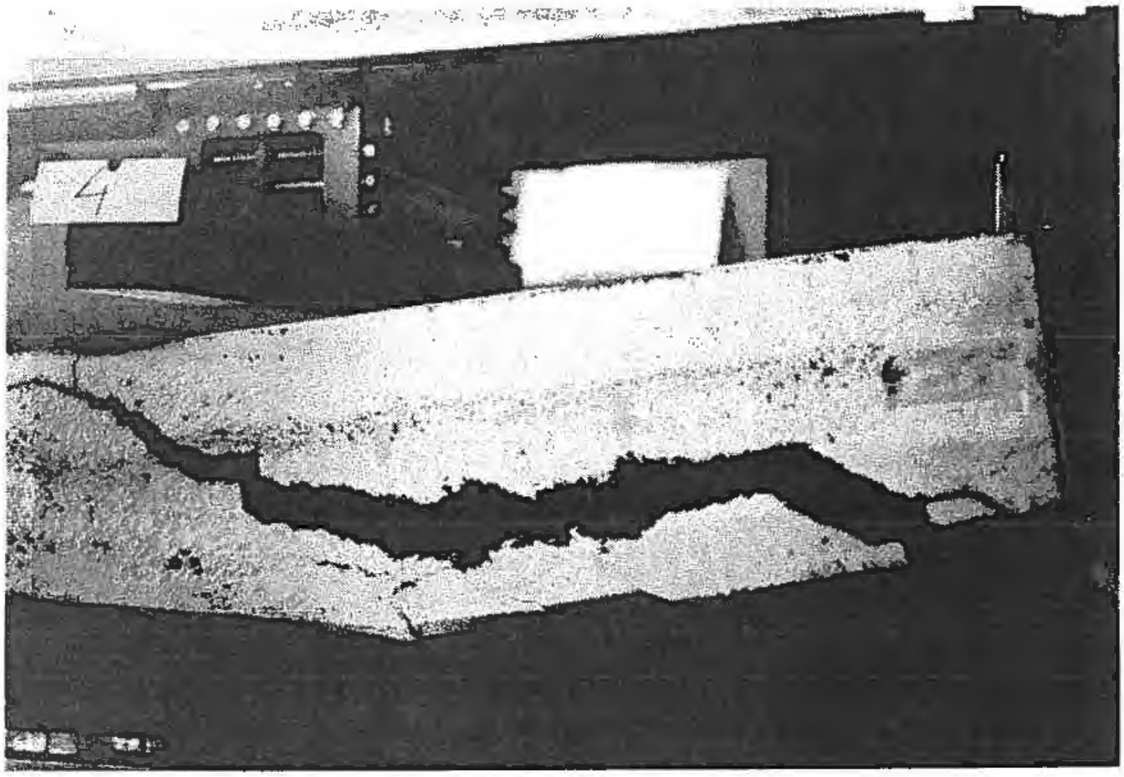

Figure 9. Typical shear failure.

5. DESIGN BY CALCULATION

Structural concrete designs are in other areas commonly documented with static formulas using the measured material parameters.

The design and products in the European marked are covered by the European CEN-standards. The members are the countries in the EEC and EFTA plus a number of associated East European states, who will implement the CEN-standards.

The Europeau concrete design standards ([1],[2],[3]), cover normalweight concrete and lightweight aggregate concrete with closed structure and are valid for both in-situ cast and precast concrete structures. The standards do not cover Aerated Autoclaved Concrete (AAC) or Lightweight Aggregate Concrete with open structure (LWAC). A special Task Committee CEN/TC177 were established in 1989 to cover the precast elements of AAC or LWAC with an open structure. The LWAC-standard [4] is issued for enquiry in 1993 along with a number of test standards, which are fairly similar to those used in the reported tests. The design rules are consistent with those in ENV1992 and will shortly be discussed in the following.

A few standards ([9],[11]) contain formulas for elements of LWAC and a homogeneous cross-sections, but no commonly accepted formulas exist for the shear capacity of elements with a sandwich cross-section, although a few references can be found ([15],[16]).

The results from the full scale testing in A/S FIBO and Dansk Leca A/S (two Danish producers) over the last 5 years can be used to evaluate the formulas for the bending and shear capacities.

The test results show that the experimental bending capacity corresponds well with simple static estimates based on internal lever arm (h_{int}) and the ultimate tensile strength (f_{ut}) of the reinforcement

$$M = A_s \cdot f_{ut} \cdot h_{int} \qquad (1)$$

$$h_{int} = d - d_1/2 \qquad (2)$$

The formulas for the shear capacity need, however, some further considerations. The shear capacity is estimated according to ([1],[3]) as:

$$V_r = \tau_r \cdot K \cdot (1.2 + 40 \cdot \phi) \cdot b \cdot d \qquad (3)$$

where

$$\tau_r = 0.125 \cdot f_{bt} \qquad (4)$$

$$K = 1.6 - d \nless 1 \qquad (5)$$

$$\phi = A_s/(b \cdot d) \qquad (6)$$

The flexural tensile strength (f_{bt}) can be documented by tests or by estimation according to the formula from ([1],[3]):

$$f_{bt} = 0.42 \cdot f_{ck}^{2/3} \cdot (0.4 + 0.6 \cdot \rho/2200) \qquad (7)$$

6. FLEXURAL TENSILE STRENGTH

The flexural tensile strength were not measured in the elements in the full-scale tests but can be estimated from the dry density and the compressive strength in the centre.

The formula (7) for the flexural tensile strength can, however, be verified from a number of tests on later elements of the same type from the same production. A prism for flexural tensile tests [13] and a cylinder for compressive tests [14] have been cut from the middle layer in a number of elements. This gives numerous sets of corresponding values of flexural tensile strength, compressive strength and dry density. The two specimens in a set are cut at the same position in the element in order to contain the same concrete quality (verified by an average variation of 2% between the dry densities of the two specimens).

The range of the tested material parameters shown in Figure 10 and 11 corresponds well with those in the full-scale tests.

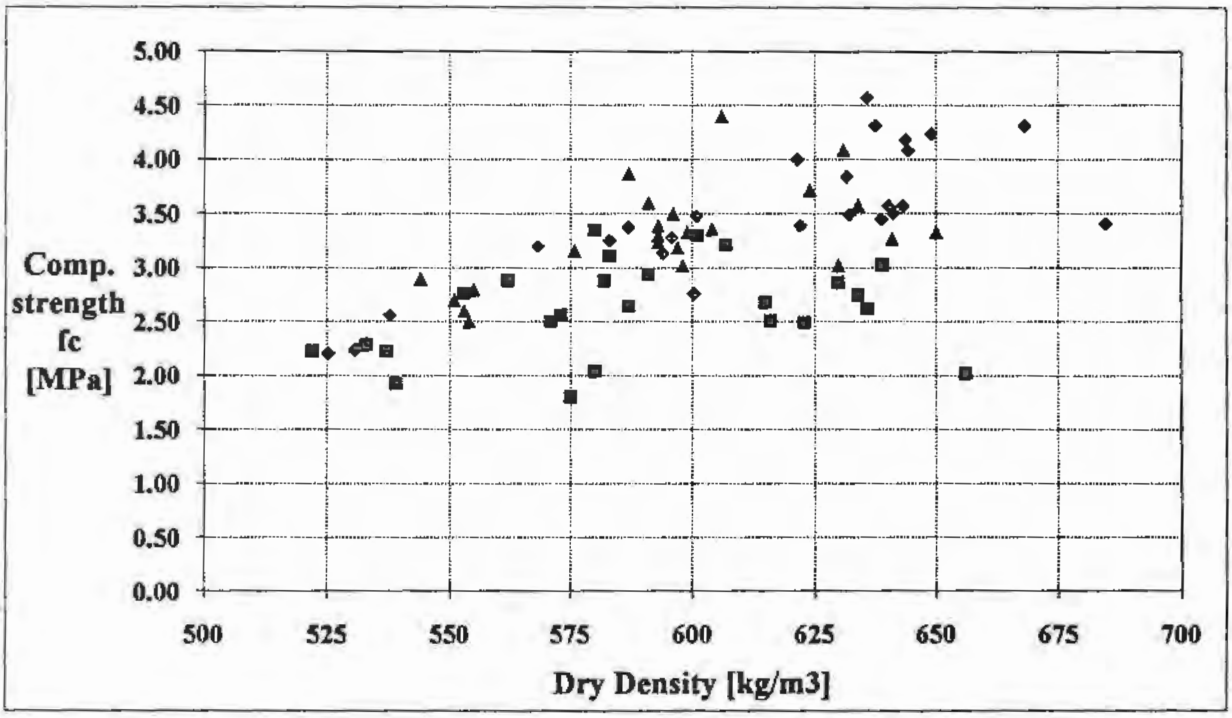

Figure 10. Compressive strength versus dry density.

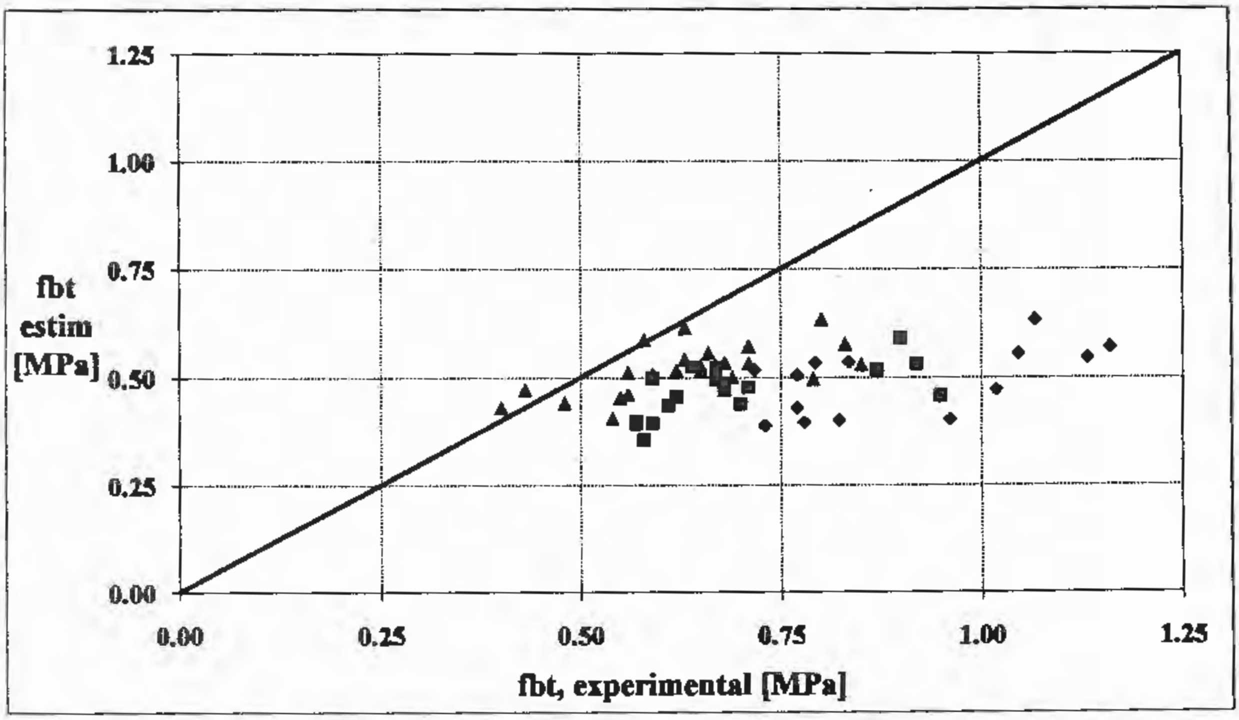

Figure 11. Flexural tensile strength, experimental and estimated versus dry density.

Figure 10 shows an almost linear relation between dry density and compressive strength in the LWAC for each producer due to variations in moisture content and element thickness. Figure 11 shows that the conservative estimate of the flexural tensile strength may underestimate the strength with up to 50%. A change in the parameters in (7) has not been suggested here, since it would not improve the correlation between experimental and estimated strength significantly unless it were done individually for each production.

7. ELEMENT SHEAR STRENGTH

The standard full-scale testing procedure includes recording of loads and displacements, self weight, failure type, cross-sectional geometry and test results for compressive strength and dry density of the middle layer.

A number of full-scale tests resulted in shear failures where the failure load can be compared to the estimated capacity (3), based on the actual cross-sectional geometry, compressive strength and dry density. The results are shown in Figure 12.

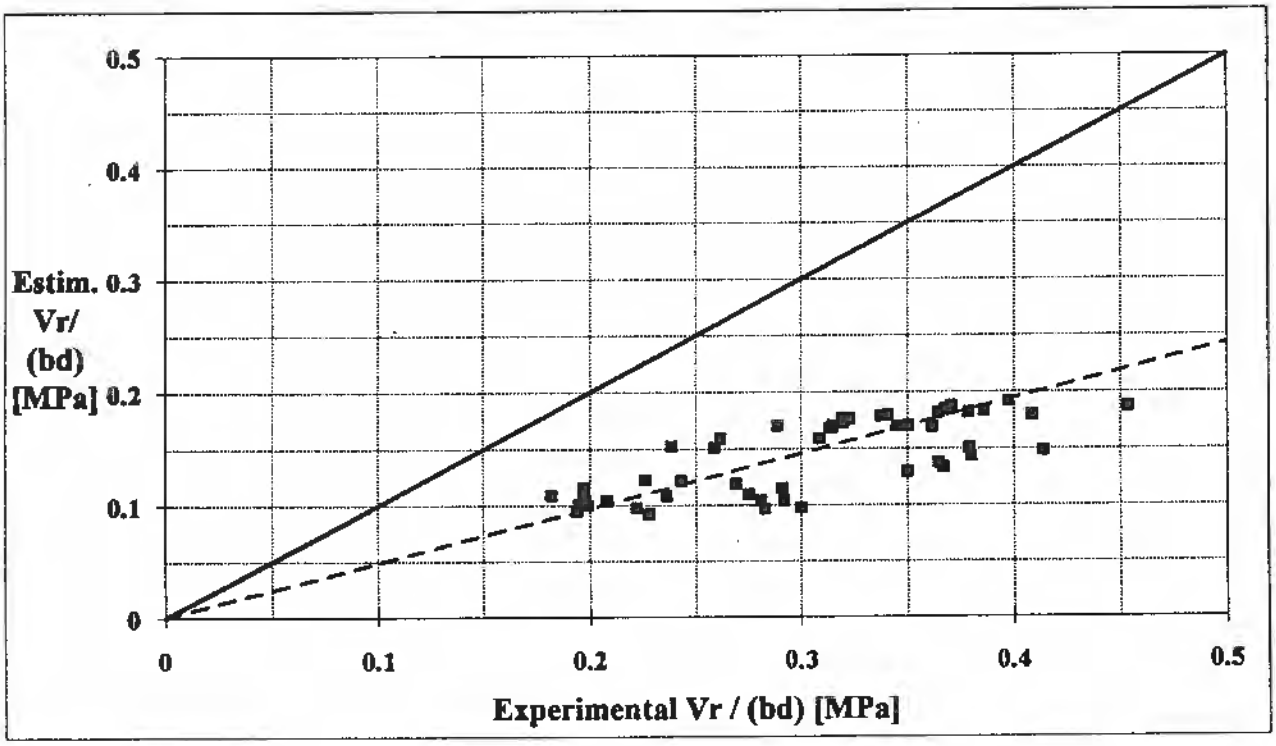

Figure 12. Shear strength of elements.

The figure shows that the estimated values are conservative with usually 50-60%. This is mainly due to the conservative estimate of the bending flexural strength, (Figure 11) which is up to 50% conservative for the LWAC used in the centre layer. A correct value of the flexural tensile strength would presumably lead to a conservative estimate at approximately 80% of the experimental level.

8. CONCLUSIONS

The prefabricated elements of LWAC are interesting because of the high performance/cost in the area of load carrying capacity, transportation, erection and insulation.

The corrosion protection principle is cheap, simple and reliable and indicates that protection in certain common environments can be obtained with far less severe requirements than currently used for the in-situ cast concrete.

The formula for the flexural tensile strength is quite conservative (50%) for the concretes tested. This is, however, acceptable due to the potentially large parameter ranges of the dry density and compressive strength in different mixes and compaction procedures and because better values can be obtained by tests.

The predictions of the shear strength based on the rules in TC177 were rather conservative, when the flexural tensile strengths were estimated. This is acceptable, since the conservativeness of the flexural tensile strength formula indicates that the shear strength prediction based on tested flexural tensile strengths would give conservative estimates at approximately 80% of the experimental level.

A more detailed investigation in which the shear strength and all the relevant material parameters are measured - including flexural tensile strength - has been initiated to give better tests of shear strength and bending flexural strength.

9. ACKNOWLEDGEMENTS

The content of this paper is much inspired by the industrial projects on material and structural optimization at A/S FIBO and the European standardisation activities. The photos and test results have been supplied by three Danish producers of lightweight aggregates and precast elements; A/S FIBO, Dansk Leca A/S and H+H Industry A/S.

The design rules, material relationships and documentation is currently being prepared by the authors in a large prestandardization project with a planned 5000 test specimens. The project is funded by the mentioned three producers and the Danish Board of Trade and Technology.

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NOTATION

A_s	Tensile reinforcement area
f_{bt}	Flexural tensile strength, mean value
f_c	Compressive strength, mean value
f_{ut}	Ultimate tensile strength, mean value
b	Width of the element
d	Effective depth of tensile reinforcement
d_1	Thickness of top layer
h_{int}	Internal lever arm between centre of compression
L	Zone and tensile reinforcement
M_r	Bending capacity of the element, mean value
V_r	Shear capacity of the element, mean value
ρ	Oven dry density
ϕ	Reinforcement ratio
τ_r	Shear strength, mean value