HIGH STRENGTH LIGHTWEIGHT-AGGREGATE CONCRETE

Dipl.-Ing. Thorsten Faust[1], *Prof. Dr.-Ing. Dr.-Ing. e.h. Gert König*[2]
University of Leipzig, Institute for Structural Engineering and Building Material
D-04109 Leipzig

SUMMARY

One research field in Leipzig deals with the design of high strength lightweight-aggregate concretes (HSLWAC). Due to the huge waveband of this concretes with all possible combinations of lightweight-aggregates and mortar matrix the formulation of general rules is difficult. Therefore both components lightweight-aggregates and mortar matrix will be investigated in detail in order to achieve a deeper understanding of the internal stress transfer and the failure mechanisms. Moreover the results of the components tests serve as input data for a computer simulation. This instrument should support the prediction and optimization of the compressive strength of LWAC.

Keywords: high strength lightweight-aggregate concrete, lightweight-aggregates, mortar matrix, internal stress transfer, brittleness

1 INTRODUCTION

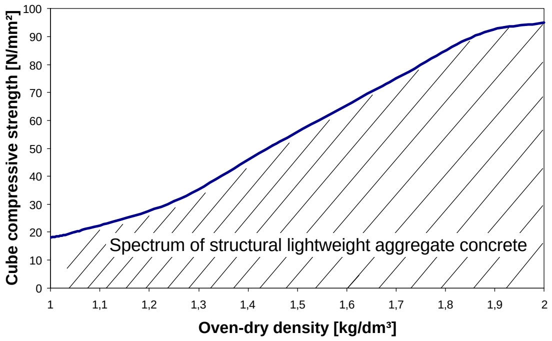

Fig.1 Spectrum of structural lightweight-aggregate concrete

Lightweight-aggregate concrete with closed structure is often called structural LWAC with regard to the applications in buildings, bridges and offshore structures. The development of new concreting materials in the last years expanded the waveband of these concretes with the aim to increase the strength or to decrease the density, respectively. Fig 1 shows the huge spectrum considering the strengths of 15 to 100 MPa and oven dry densities of 1,0 to 2,0 kg/dm³. Structural LWAC with a minimized density at a definite strength level is called HSLWAC. Thus the term “high strength” in case of LWAC is not related to the strength, but to the relation of strength to density. For all HSLWAC’s high strength mortar matrix are used so that in general the concrete strength will be limited by the efficiency of the aggregates. This fact induces a very brittle behaviour, which is independent of the strength. Consequently, the validity of the existing design rules and calculation models have to be proven with regard to the use of HSLWAC in order to adjust possible limits of applications.

---

[1] PhD student
[2] Professor in Structural Engineering

2 LIGHTWEIGHT-AGGREGATE CONCRETES IN COMPRESSION

The stress/strain behaviour of LWAC in compression is, compared to normal density concretes (NC) of the same compressive strength, generally characterized by a linear ascending branch, a lower E-modulus and less ductility in the post-failure region. These characteristics are usually more pronounced with increasing compressive strength and decreasing oven dry density. Therefore HSLWAC not only comprises LWAC with a high strength, but also LWAC with a low density.

Fig.2 shows a stress-strain curve of a strain controlled compressive test with a cylindrical specimen. After longitudinal cracking (Fig.3a) pieces of concrete spall off the cylinder (Fig.3b). This phenomenon was particularly observed in case of ALWA-concretes (**A**ll **L**ight **W**eight **A**ggregates). The reduced cross sectional area requires a quick unloading to avoid a sudden failure. The decreasing load allows an elastic expansion of the undestroyed regions outside the damage zone. In case of brittle concretes combined with a small damage zone in relation to the regions outside this fact causes a so called snap-back. In consideration of the low modulus of elasticity this effect is valid for all HSLWAC.

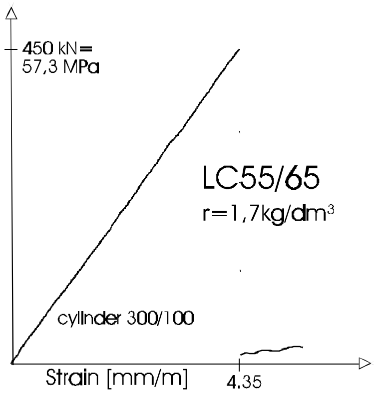

Fig. 2 Stress-strain curve using strain control

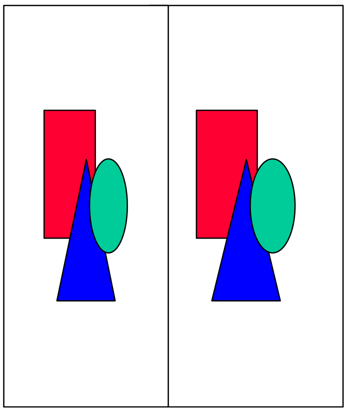

Fig.3 Different fracture states
a) longitudinal cracks
b) spalling of concrete pieces

Due to the snap-back effect the failure phenomena of the specimen must be controlled by other suitable means. The first experiments were performed with a combination of axial and circumferential strain control. This test setup was already used successfully with HSC. But in case of LWAC, partly unstable softening occurred as well, which probably was caused by the low modulus of elasticity (Fig.4). For this reason a control method, where a considerable portion of the E-modulus will be compensated, had to be taken into consideration. This seems to be a promising solution in case of LWAC [1,2].

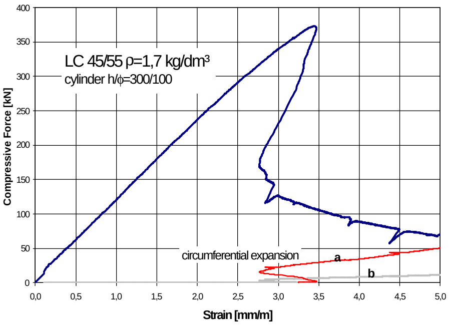

Fig. 4 Stress-strain curve using axial and circumferential strain control

Fig.5 shows the principle of the control method. A linear combination of deformation and force is chosen as the feedback signal for a closed-loop servo-controlled system:

$$F_S = d - \frac{F}{K} \quad .$$

Geometrically this control corresponds to a rotation of the axis with the angle Φ=1/K, which allows a steadily increasing feedback signal, if the stiffness value K is chosen

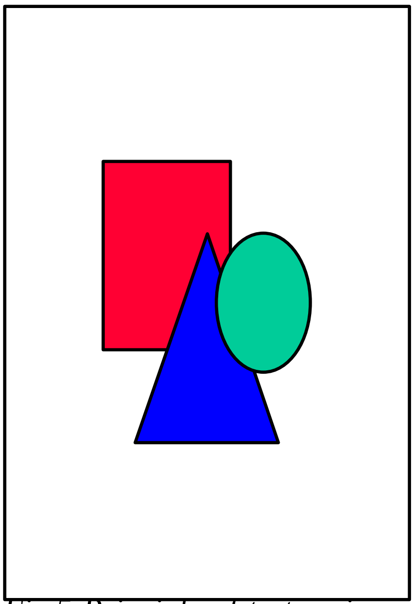

Fig.5 Principle of tests using a linear combination of force and deformation as control variable

between K_{pre} and K_{post}. In this context I would like to express my gratitude to Professor Marti Marti from the technical university in Zürich (ETHZ) and his scientific assistants, Heinrich Schnetzer and Kyrill Sokolov, who conducted the first tests with two different LWAC mixtures, for their outstanding support. Fig.6 shows stress-strain diagrams of concretes with different densities at three different strength levels. All of these stress-strain curves indicate a stable descending branch as a sign of a controlled post-failure region. Therefore the diagrams demonstrates that the described test method presents a successful way to obtain the full stress-strain curves of HSLWAC.

Fig.6 also illustrates a very brittle behaviour, also for LWAC of moderate strength, if aggregates of moderate density are combined with a high strength cement matrix. This observation confirms the definition of HSLWAC given in the introduction.

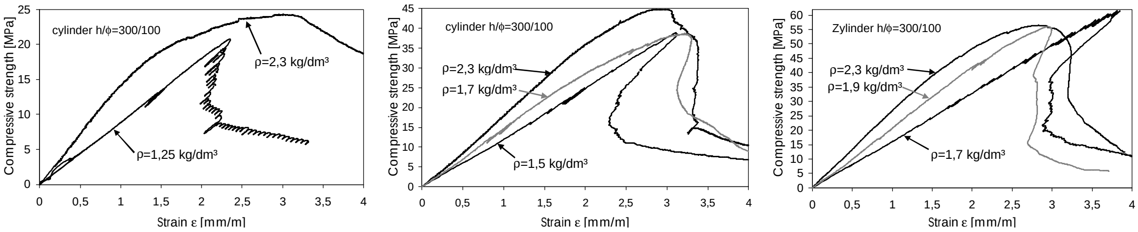

Fig.6 Stress-strain diagrams of concretes with different densities and strength

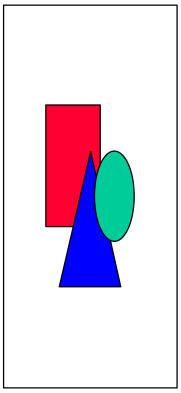

Fig. 7 Sliding mode of failure

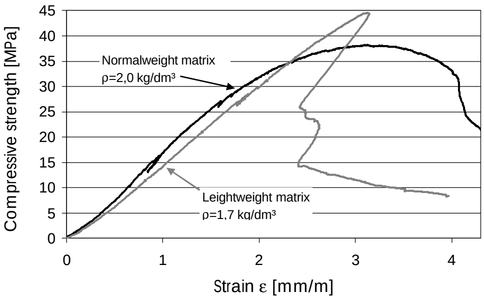

Fig.8 Stress-strain diagram of mortar-matrix with natural and lightweight fine aggregate

The different densities in Fig. 6 represent LWAC with lightweight fine material (ALWAC, lower density), LWAC with natural fine material (middle density) and normal concrete (ρ=2,3kg/dm³). Typical for the LWAC with natural fine material and a strength over 35 MPa was a sliding mode of failure (Fig.7). In these cases only the undestroyed regions outside the damage zone expanded due to the decreasing load (moderate snap-back) in contrast to Fig.3b, where a horizontal damage zone can't be defined in that way and where the extension over nearly the whole specimen length causes an extremely snap-back effect. Moreover the characteristics of the different mortar-matrix also influence the properties of the respective concrete with regard to the linearity of the ascending branch, the ductility in the post-failure region, and finally the failure mode (Fig.8).

The European standard ENV 1992-1-4 EC2 [3] recommends a bi-linear stress-strain diagram (Fig.9) with a constant strain at the break point (2‰) and a constant ultimate strain of ε_{lcu}=3.5 ‰. Fig.6 demonstrates that particularly in case of ALWAC the length of the yield plateau seems to be overestimated in [3]. In the next months, additional tests will follow to investigate the behaviour under sustained load. The purpose of this study is to find a realistic formula which takes into account the dependence of ε_{lcu} on compressive strength and oven dry density.

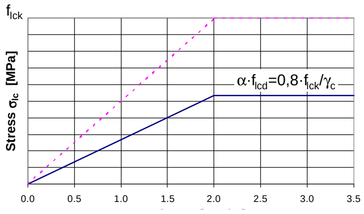

Fig.9 Bi-linear stress-strain diagram given in [3]

Contrary to the German standard DIN 4219, most of the international standards take into account that the modulus of elasticity of LWAC depends on the compressive strength and the density. The tests conducted so far with different aggregates confirm both influences. Fig. 10 shows one evaluation of these results compared to values calculated by means of the E-modulus given in EC 2 T.1-1 multiplied with a reduction factor $\eta=(\rho/2,4)^2$, where ρ denotes the oven dry density. Furthermore, investigations will follow in order to find the reduction factor with the best possible agreement.

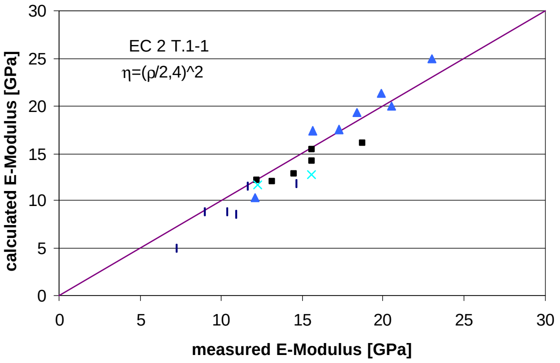

Fig.10 Comparison between calculated and measured values of E-modulus of LWAC

In general, the development of strength with time is faster in case of LWAC compared with NC, particularly above the limit strength of the LWAC (see Fig.14). Fig.11 shows an evaluation of self tests and various publications according to the equation given in Model Code 1990. Therefore the post-hardening is smaller for LWAC.

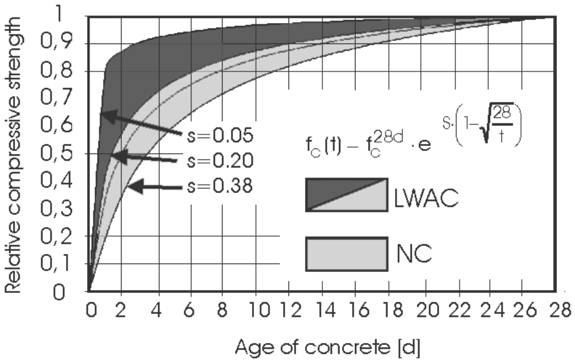

Fig.11 Development of compressive strength with time for NC and LWAC

The influence of the specimen-shape on the compressive strength tend to be smaller in case of LWAC. Typical values for the ratio between the compressive strength of cylinders and cubes are slightly above 0,9. The reason for that is the smaller effect of the lateral expansion restraint due to the smaller lateral strain of LWAC at the maximum load.

3 MODELLING OF A LWAC-CUBE UNDER COMPRESSION

An axial compression test of a 100mm LWAC-cube should be simulated by means of SBETA, a program for nonlinear finite element analysis. Several publications confirmed the strong bond forming between the matrix and the expanded aggregates such that failure would be either through the paste or through the aggregate. Thus, the concrete was modelled as a two-component material for a two-dimensional computer simulation. In this simulation a plate was cut from the cube. The laterial strain on the upper and lower surface of the plate was eliminated. The load was being applied on a steel bearing plate controlled by the strain. The volume of the grains was chosen with V_p=40% of the concrete volume according to self experiences. The size and the distribution of the 121 pellets were determined by a statistical evaluation. Fig.12 shows the FE-mesh with all geometrical joints. To overcome the influences of the mesh and three-dimensional effects, previous analyses were carried out to calculate the necessary input value of the compressive strength of the matrix in a one-component system. In this way increased matrix strength data were added to the program to reach the real value of the axial compression tests with various matrixes.

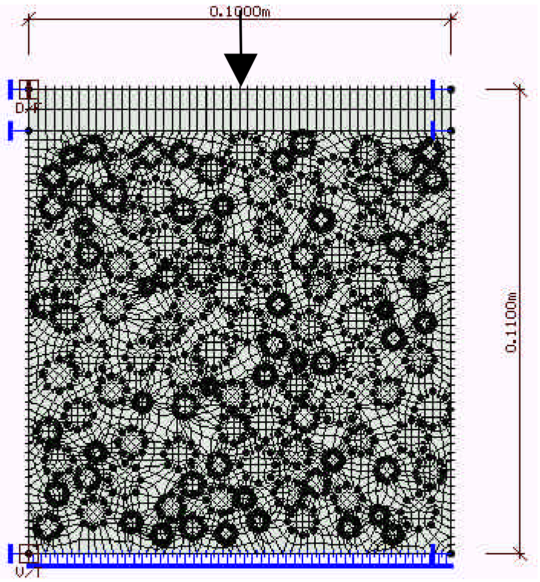

Fig.12 FE-mesh with geometrical joints

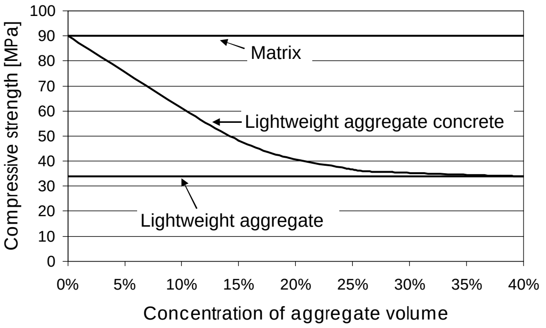

Fig.13 Relation between concentration of aggregate volume and LWAC compressive strength

At the beginning of the simulation the lack of information about the properties of both components was indicated in consideration of the stress-strain relation in the compression and tensile region. In particular, the compressive strength of the aggregates was a dominate element with regard to the strength of the LWAC-cube. Fig. 13 shows, that in spite of a high strength matrix the strength of the cube was equal to the strength of the grains, if the aggregate volume exceeded 40% of the concrete volume. The other way around, this result can be use to define the compressive strength or efficiency of LWA respectively.

Fig.14 shows the evaluation of the analysis. The known form demonstrates the relationship between the compressive strengths of the matrix and the LWAC and additionally in comparison with laboratory results. The simulation also demonstrates the different internal stress transfer and the failure mechanisms of LWAC and NC. In general the aggregates in LWAC have a lower stiffness than the mortar matrix in opposition to NC. Thus, compressive loads are mainly carried by the stiffer mortar matrix

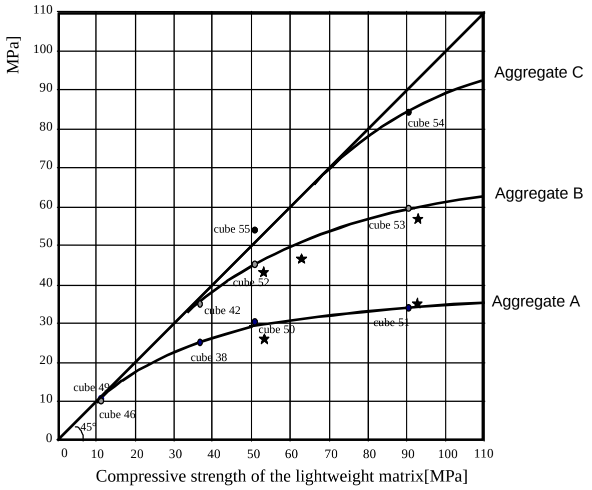

Fig.14 Relation between the strengths of matrix and LWAC

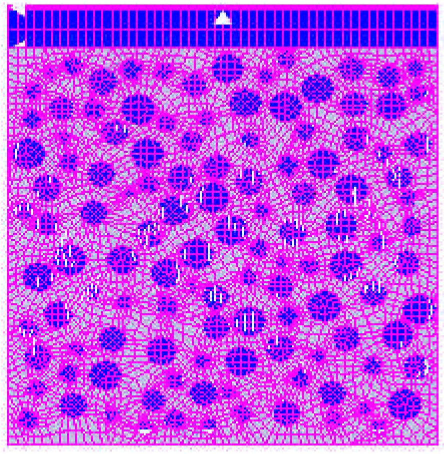

Fig.15 Crack propagation in LWAC

corresponding to the stiffness relationship between matrix and aggregates, which causes transverse stresses in the aggregates and in the matrix. Finally, failure occurs after exceeding the tensile capacity of the aggregates. The cracks usually propagate straight through the aggregate particles (Fig. 15). The smooth fracture surfaces transfer less stress and initiate a brittle failure.

4 PROPERTIES OF THE COMPONENTS

The important meaning of the component properties with regard to the simulation was already mentioned. Furthermore, their knowledge can be helpful for a better understanding of the internal stress transfer and for the optimization of the strength. Fig. 16 shows for instance the result of wedge splitting tests with LWAC's consisting of different components. Obviously there seems to exist a strong connection between the combination of the components and the fracture energy.

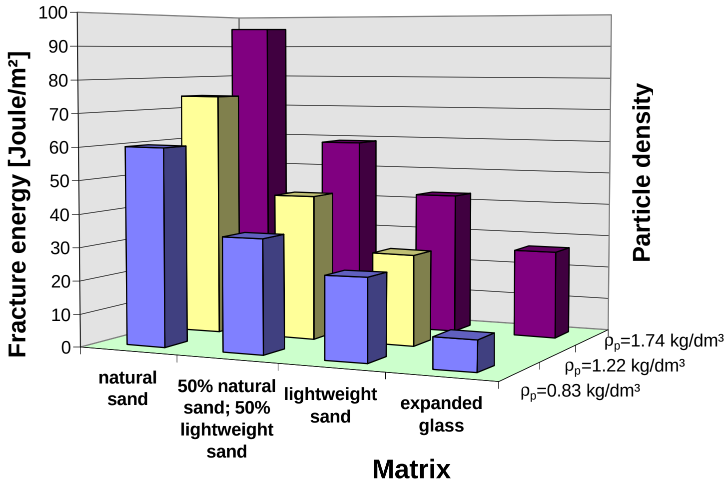

Fig. 16 Fracture energy for LWAC with different components, investigated in wedge splitting tests

4.1 Properties of lightweight aggregates

There is a wide range of different lightweight aggregates, which differ in the raw material, density, shape, outer skin and water absorption. In spite of this fact, their properties can be estimated with simply formulas, which in general depend on the particle density. In this context we tested several aggregates (expanded clay, shale and glass, sintered fly ash, pumice) with regard to the compressive and tensile strength. Fig. 17 and 19 demonstrate that there are obviously connections only with slight dependence on the aggregate type. Fig. 17 also shows the necessity to use a high-strength matrix in order to determine the compressive strength of the particles. The test methode, measuring the crushing resistance, can not be recommend to achieve a statement about the efficiency of the aggregates.

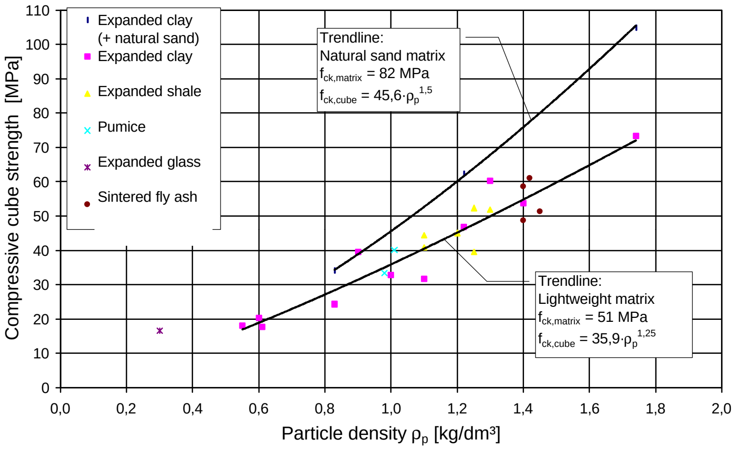

Fig.17 Relation between cube compressive strength of LWAC and particle density in dependence on the matrix strength

For the tensile strength of pelletized aggregates, we developed a new testing arrangement shown in Fig. 18. Twelve grains were glued in the openings of two opposite plates and the tensile force to the fracture area were related. In this way we achieved the lower limit of the tensile strength, since a premature failure of a single grain can't be excluded. Fig.19 shows that the particle tensile strength increases exponential with increasing particle density. Thus, this fact explains the increasing fracture energy with increasing particle density.

Fig.18 Testing arrangement for the particle tensile strength

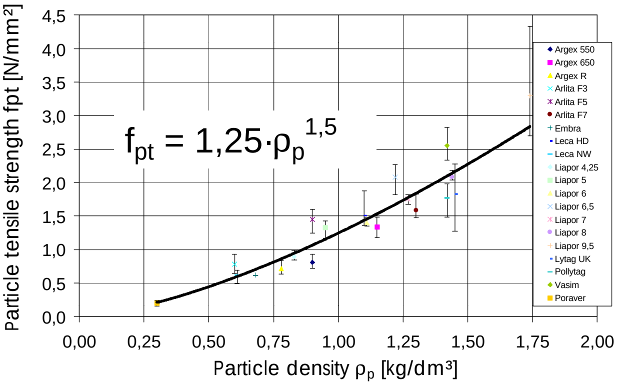

Fig.19 Relation between particle tensile strength and particle density of 7mm grains

The dynamic particle modulus of elasticity was estimated according to Schütz as:

$E_{dyn,p} = 8000 \cdot \rho_p^2$.

4.2 Properties of mortar matrixes

The influences of the different matrixes on the shape of the stress-strain curves were already mentioned. Additional important aspects are their differences with regard to the modulus of elasticity and the ratio between compressive strength and tensile strength. For instance, the internal stress transfer is influenced considerably by the stiffness ratio of both components. However, the properties of the lightweight matrixes are almost unknown. This is the reason that a study was started to investigate different matrixes. Intermediate results will be published at a later moment.

5. CONCLUSIONS

The formulation of general design rules for LWAC requires a deeper understanding of both components lightweight-aggregate and mortar matrix. There are numerous types of each component and their combinations, which have a decisive effect on the behaviour of LWAC. Therefore the investigation of different components was started, which complement the tests with LWAC's in order to

- support the evaluation and explanation of the concrete tests
- optimize the properties of LWAC's
- predict the concrete behaviour by means of a computer simulation.

6. ACKNOWLEDGEMENTS

The author would like to thank the sponsor, Lias Franken, for financial support for these investigations.

7. REFERENCES

[1] Okubo, S., Nishimatsu, Y.: Uniaxial Compression Testing Using a Linear Combination of Stress and Strain as the Control Variable; Int. J. of Rock Mech., Min. Sci. & Geomech., Abstract., Vol. 22, No.5, 1985, pp. 323-330

[2] Jansen, D.C., Shah, S.P.: Effect of Length on Compressive Strain Softening of Concrete – Journal of Engineering Mechanics. Jan., 1997

[3] ENV 1992-1-4 EC2; “Design of LWAC with closed structure”