Fracture mechanical behaviour of lightweight aggregate concrete

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ABSTRACT: In a recent research project the fracture mechanical behaviour of several lightweight aggregate concretes with strengths ranging from 20 to 100 N/mm² and dry densities from 1.3 to 1.8 kg/m³ were investigated in order to determine the specific fracture mechanical parameters, such as fracture energy, characteristic length, uniaxial tensile strength and softening behaviour. This paper will give an overview on generalized statements and summarises the main results.

Keywords: Lightweight aggregate concrete, fracture mechanical parameters

1 INTRODUCTION

Lightweight aggregate concrete (LWAC) is generally characterized by a more brittle behaviour than normal weight concrete (NWC) with a comparable compressive strength. One reason for this behaviour is related to the reduced aggregate interlock, because the cracks usually propagate straight through the aggregate particles. Thereby, the concrete-to-concrete friction as one of the mechanisms of shear transfer is reduced in the case of LWAC. The brittleness of concrete is usually evaluated by means of the post failure behaviour in tension, which is governed by the stress vs. crack width relation (σ-w relation), the so-called softening behaviour. It is described by the tensile strength $f_{ct,ax}$ the maximum crack width w_c and the fracture energy G_F, which corresponds to the area under the stress vs. crack width curve. The knowledge of these parameters makes possible estimations for instance about the concrete-to-concrete friction, the dowel-action of the longitudinal reinforcement, the shear capacity and the brittleness in compression and tension. So the σ-w relation is a basic property of concrete, which serves as input data for the analysis of many complex actions in concrete.

The most favorable method to obtain the softening behaviour is the strain controlled uniaxial tensile test as in this case the σ-w relation is obtained directly from the measured curve. Moreover, frictional actions and stress gradient are minimized in comparison to the flexural tensile test. Additional to the uniaxial tensile test, the wedge splitting test (WST) also offers an appropriate method for investigating the softening behaviour.

Previous publications [1, 2] concerning the softening behaviour of LWAC were only related to LWAC with natural sand (Semi or Sand LWAC). However, it is known that the dense sand grains are able to resist the propagation of cracks, whereas lightweight fine aggregates are supposed not to do so. Therefore, considerable differences exist between SLWAC and all LWAC (ALWAC). Normally for the description of the load bearing capacity of lightweight aggregate concrete in tension only the state up to the tensile strength will be considered. With regard to the fracture mechanical behaviour of LWAC it has to be known how far the concrete is able to transmit tensile stresses over cracks after the tensile strain has been exceeded.

The relationship between tensile stresses and displacement shows the following characteristic processes: 1) shortly before reaching the maximum load the LWAC shows nearly an ideal elastic material behaviour. During those quasi-elastic deformations micro-cracks occur which are uniformly distributed over the specimen, 2) however, in the end the micro-cracks accumulate at the weakest point of the tensile test specimen (accumulation zones) and the strength is reached immediately afterwards. Thus, the energy dissipation is not restricted to the fracture areas (linear-elastic fracture mechanics) but includes the adjacent areas too, the so called fracture process zone. Non-linear fracture mechanics is hence also applicable to lightweight aggregate concrete.

After the maximum value has been exceeded the failure of the test specimen can be avoided by a reduction of the tensile stress alone. A discrete individual crack occurs with increasing deformation while the micro-cracks outside this area gradually close again as stress is released. The tensile force in the individual crack is transmitted through material bridges and grain links, and decreases with increasing crack width.

To cover a large spectrum for different combinations of fine and coarse aggregates a total of 15 lightweight aggregate concretes have been tested. Table 1 gives a survey of the employed aggregates. As a main aggregate expanded clay was used in the fine as well as in the coarse fraction. Additionally, expanded slate and glass are used to extend the investigation program to evaluate the influences of the different aggregates on the specific fracture mechanical behaviour of the LWACs. As it is known that expanded glass increases the brittleness and decreases the strength this aggregate was used for LWACs with low compressive strength. Table 1 shows also the measured densities ρ_a of the coarse aggregates.

Table 1. Survey of tested concrete matrixes

coarse aggregates	fine aggregates	strength of matrix	series No.
exp. clay [1)]	exp. clay	moderate	1
exp. clay [1)]	exp. clay/nat. sand	high-strength	2
exp. clay [1)]	nat. sand	high-strength	3
exp. clay [1)]	exp. glass	low	4
exp. clay [2)]	exp. clay	moderate	5
exp. clay [2)]	exp. clay/nat. sand	high-strength	6
exp. clay [2)]	nat. sand	high-strength	7
exp. clay [2)]	exp. glass	low	8
exp. clay [3)]	exp. clay	moderate	9
exp. clay [3)]	exp. clay/nat. sand	high-strength	10
exp. clay [3)]	nat. sand	high-strength	11
exp. clay [3)]	exp. glass	low	12
exp. slate [4)]	exp. slate	moderate	13
exp. slate [4)]	exp. slate/nat. sand	high-strength	14
exp. slate [4)]	nat. sand	high-strength	15

[1)] $\rho_a = 0.79$ kg/dm³, [2)] $\rho_a = 1.19$ kg/dm³
[3)] $\rho_a = 1.70$ kg/dm³, [4)] $\rho_a = 1.28$ kg/dm³

Figure 1 gives the relation between the concrete compressive strength $f_{lc,cyl}$ for the employed LWACs and their respective dry densities ρ_{dr}. From a theoretical point of view an average line is given to illustrate the correlation of the results.

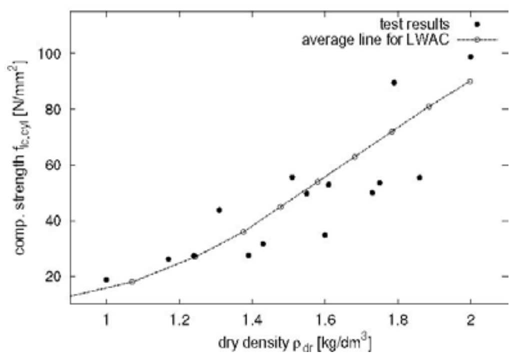


Figure 1. Relation between $f_{c,cyl}$ and ρ_{dr}

2 SENSITIVITY TO NOTCHING

A material is considered sensitive to notching if the uniaxial tensile strength of a notched body σ_n related to the net area is significantly smaller than the tensile strength of an un-notched body. Usually notch sensitivity applies to homogenous materials, including hardened cement paste. However, concrete is generally considered to be not susceptible to notching. In bending tension tests, for example, Shah and McGarry in [3] were able to determine sensitivity to notching of hardened cement paste only, but not of mortar, normal weight concrete and lightweight aggregate concrete with natural sand.

Considering the unobstructed spreading of cracks in matrices with lightweight sand a similar behaviour should be expected in ALWAC as in hardened cement paste. For this reason, the sensitivity to notching of a lightweight aggregate concrete with expanded clay sand was investigated [4]. For this purpose lightweight concrete cylinders with natural sand and lightweight sand were prepared. The test values obtained show that lightweight concretes are not sensitive to notching, above all when considering that the measured tensile strength of un-notched samples usually tends to be rather overestimated by “wild” fracture areas. Furthermore, the results show the often observed re-increase of the tensile strength σ_n with increasing notch depth, which is explained in [5] by a model law.

The result of this investigation is so far surprising, as even for lightweight aggregates without natural sand, an effect on unstable fracture growth is observed, although the porous lightweight aggregate obviously does not strongly resist the opening of cracks. So it can be stated that tension tests of notched test specimens made of lightweight aggregate concrete with natural sand or expanded clay or expanded slate sand are useful.

Whether this statement also applies to lightweight aggregate concretes with expanded glass, is however very questionable considering the brittle behaviour of expanded glass matrices [4].

3 UNIAXIAL TENSILE STRENGTH

To determine $f_{lct,ax}$ without any influences of notching an optimized specimen mould was created to allow the performance of uniaxial tensile strength test. The form resembles the "dog-bone-form" (Fig. 2, 4). In comparison to other moulds this one is axially symmetric and optimized for force- and strain-controlled tensile tests. The design of tensile test mould considers the following:

- developing a uniaxial stress condition,
- small measurement length by complete covering of the fracture process zone (snap-back-problem),
- no influence caused by notch effects,
- no failure occurrence out of the measurement length.

With a finite element analysis the tensile stress distribution in the specimen was verified. At first the influence of strain disability near the loading area was studied. With an assumption of linear elastic material behaviour, the influence of the variation of the cross section and the height of the specimen was investigated.

To prevent an accelerated drying of the test specimens they were covered with a foil shortly before testing ($f_{lct,ax,wet}$). Additionally test were carried out without a coverage ($f_{lct,ax,dr}$). The difference is shown in fig. 3.

Before testing the specimen they have to be prepared. At the bottom and at the top steel plates were glued for the load application.

Most specimens have their failure plane in the middle area. Only five of 45 specimens failed near the steel plates.

The reason was the low load bearing capacity of the glue in connection with little material defects. All failed specimens show a nearly plain cross section.

Figure 2. New shaped test specimens (1)

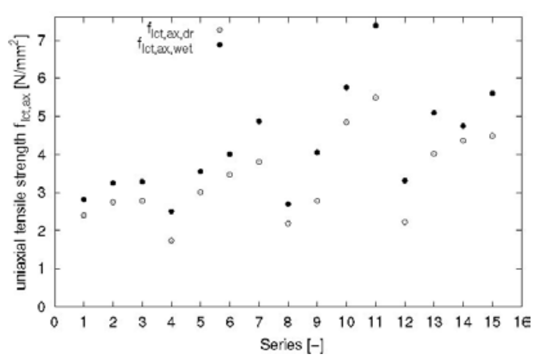


Figure 3. Uniaxial tensile strength $f_{lct,ax}$ (dry, wet)

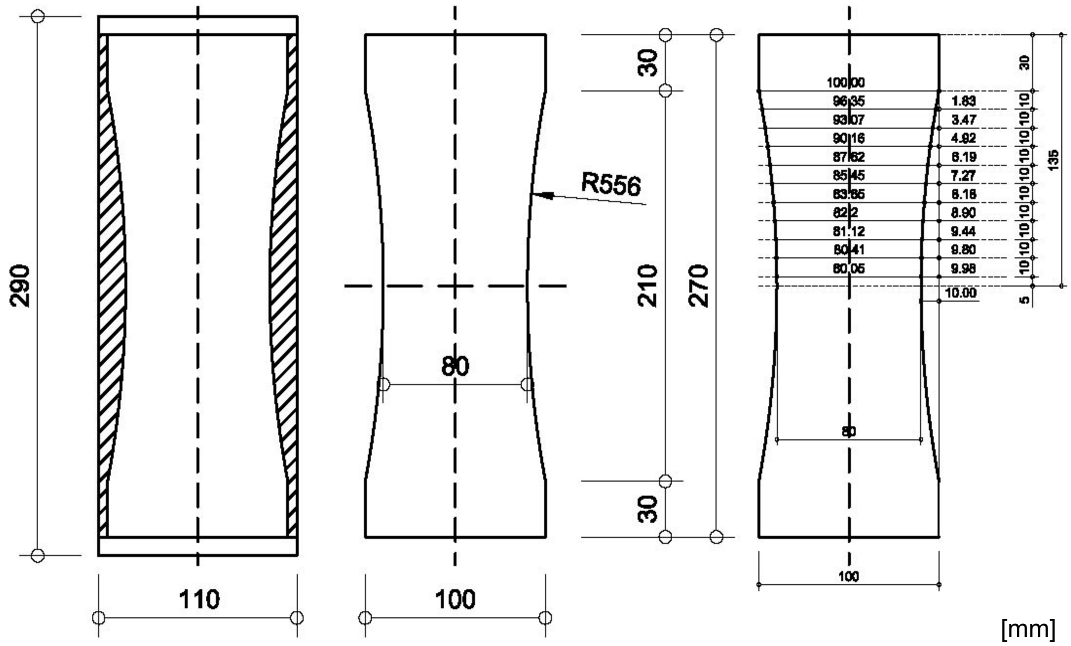


Figure 4. New shaped test specimens (2)

4 FRACTURE ENERGY

The energy per area needed for the complete separation of a concrete body is designated as the specific fracture energy G_F. The influence of lightweight aggregate and the matrix on the fracture energy of lightweight aggregate concrete was investigated by means of wedge splitting tests, where concrete bodies with predetermined cut notch are tested under controlled deformation. For this purpose, a prismatic specimen with pre-sawn gap is set in the centre of a line bearing, and equipped with two steel plates on both sides, to which two rollers each are attached. The principle of wedge splitting tests is shown in Figure 5.

The wedges are pressed between the bearings in order to split the specimen into two halves. The splitting force F_s is the horizontal component of the force acting on the bearings. The horizontal displacement at the level of F_s is monitored using two linear variable differential transformers (LVDT), which also control the test in order to record the post-peak tensile behaviour.

By now the specimen dimensions have not been standardised by any code although the test result depends significantly on the size, as the fracture energy increases with growing ligament area and decreasing eccentricity of the strain.

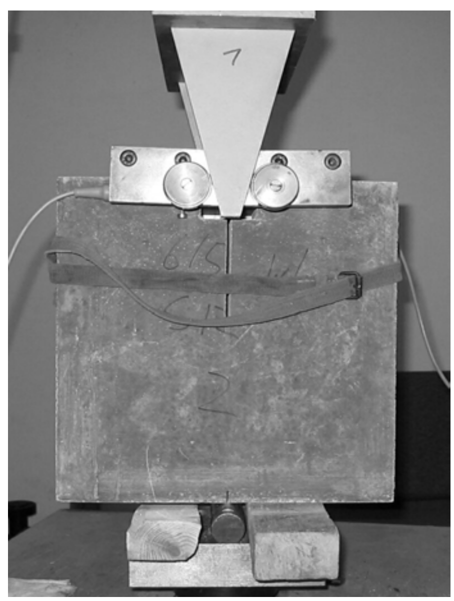
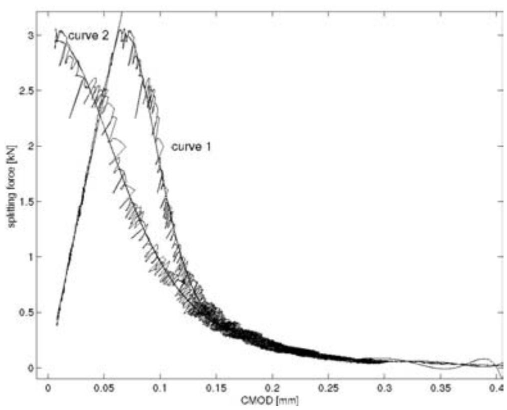


Figure 5. Wedge Splitting Test

The prism normally used stems from an investigation by Slowik, which mainly studies the influences on the fracture energy obtained from wedge splitting tests [6].

The result of the wedge splitting test is the relationship between the splitting force and the displacement (Fig. 6). The area under the curve divided by the projected fracture area corresponds to the fracture energy.

Figure 6. Splitting force vs. CMOD



The tests with varying coarse aggregates, admixtures and additives show obvious similarities independent of the lightweight aggregate used. While mixtures with natural sand allow for a crack opening of approx. 2 mm the concretes with lightweight sand matrix could achieve at best half this value. In general the brittleness of the material is increased by the addition of silica fume. The coarse aggregate controls the maximum splitting force only by its tensile strength, and so it also influences the fracture energy.

The wedge splitting tests proved that the magnitude of the fracture energy is decisively determined by the maximum splitting force, which on the other hand depends on the tensile strength of the concrete. Consistently Hordijk [7] develops formulae for the estimation of the fracture energy of normal-weight concrete (NWC) and lightweight concrete, without differentiation with regard to the used matrix, as a function of the uniaxial tensile strength.

However, a comparison with test results confirms that the applicability is restricted to lightweight aggregate concretes with natural sand (SWLAC):

$$\text{NWC: } G_F = 24+26\cdot f_{ct} \quad (1)$$

$$\text{SLWAC: } G_F = 24+16\cdot f_{ct} \quad (2)$$

G_F in [N/m], f_{ct} in [N/mm²]

Walraven et al. [8] made tension tests with normal weight concrete and SLWAC. The comparison of the test results with the approach of Hordijk shows an excellent correspondence. If however lightweight concretes with lightweight sand are included in the comparison the measured values are significantly overestimated by the prognosis according to the above mentioned formula.

For this reason it is suggested on the basis of the results of wedge splitting tests conducted by Faust [4] the following equation for ALWAC:

$$\text{ALWAC: } G_F = 16\cdot f_{ct} \quad (3)$$

G_F in [N/m], f_{ct} in [N/mm²]

5 SOFTENING BEHAVIOUR

In addition to the fracture energy, the softening behaviour is important for the realistic description of the fracture formation in concrete. It is shown in the form of tensile-stress crack-opening relation. Cornelissen, Hordijk and Reinhardt [1] made numerous elongation controlled test with normal-weight concrete and lightweight concrete with natural sand.

Accordingly, the principal differences in SLWAC apart from the tensile strength are the lower tension transmission between the opposite sides of a crack opening of 20 µm and in the smaller critical crack opening w_c, where the tensile stresses transmitted in the cracks, reaches the zero value. Tests on lightweight concrete with lightweight sand were not included.

Our own tests show that there where significant differences between SLWAC and ALWAC. The reason for the clear difference between SLWAC and ALWAC with regard to the critical crack opening is based on the obstructed spreading of the cracks in the matrices with natural sand. As natural sand grains offer a much higher resistance to the further continuation of cracks than porous sand the crack has to avoid the obstruction in this case. As a result, the roughness of the inside crack surface is necessarily increased so that the friction and sliding processes become more important (fig. 7).

This is the reason why lightweight concretes with natural sand are able to transmit tensile stresses over larger cracks than ALWAC.

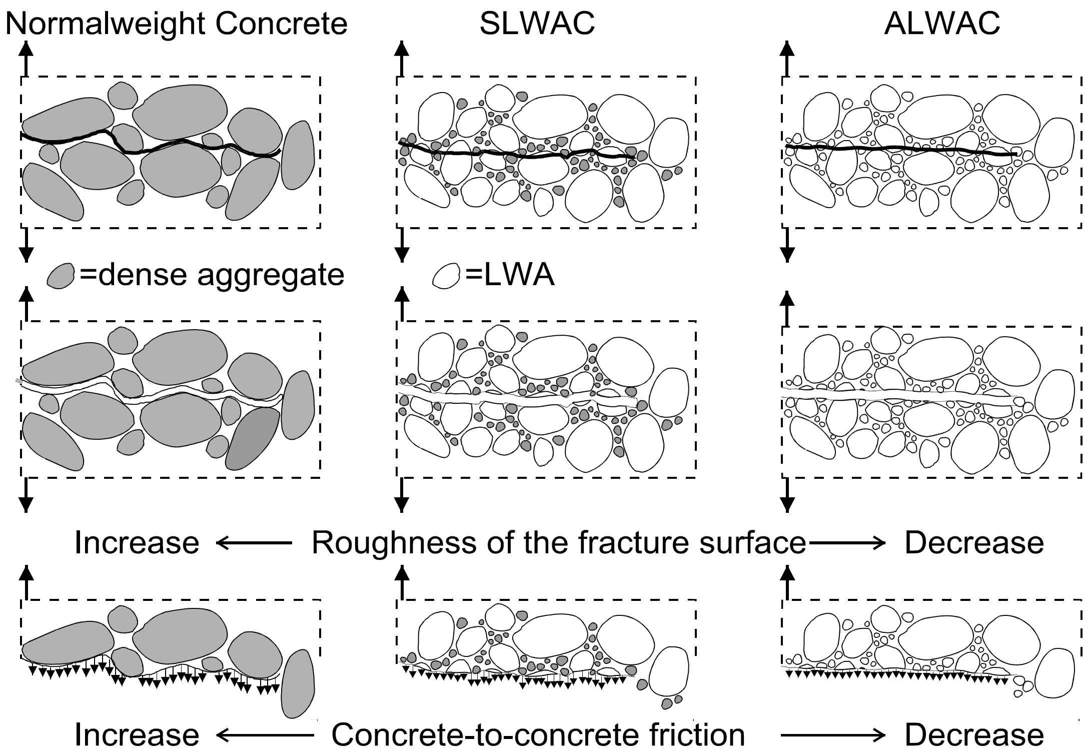


Figure 7. Influence of the aggregates on the softening behaviour of LWAC [4]

The difference between normal weight concrete and lightweight concrete in the primary bearing effect is rather smaller, although it is reasoned by different fracture mechanisms in both of them. A tendency can be seen from the results of a simulation [4] that the primary release leg is dropping steeper the lighter the matrix is.

6 CHARACTERICTIC LENGTH l_{ch}

Hillerborg, Modéer and Petersson [9] introduced the characteristic length l_{ch} as a unit for the ductility of a material. In a tension tests l_{ch} exactly corresponds to the half of a part of the specimen length wherein the energy is stored which is needed for the generation of a fracture area. By this definition, the characteristic length for lightweight aggregate concrete can be determined by equating the deformation energy and the fracture energy:

$$l_{ch} = \frac{G_F \cdot E_{lc}}{f_{lct,ax}^2} [\mathrm{mm}] \tag{3}$$

G_F in [N/mm], E_{lc} in [N/mm²], $f_{lct,ax}$ in [N/mm²]

Thorenfeldt indicates characteristic lengths for several concretes [10]. As, so to speak, l_{ch} also reflects the fullness of the standardised tensile-stress crack-opening relation, it decreases with increasing compressive strength and decreasing dry density of the concrete.

According to our own tests the brittleness of lightweight aggregate concrete increases with decreasing grain density of the coarse and fine aggregate. As expected the shortest l_{ch} is obtained in LWAC with expanded glass, and the largest one in SWLAC. The highest value of approx. 230 mm was determined, related to the density of the coarse grain, with a relatively low compressive strength. Thus, they should represent almost the upper limit of the achievable characteristic length in lightweight aggregate concretes.

7 SUMMARY

Within the described research project the fracture mechanical behaviour of several lightweight aggregate concretes (LWAC) was investigated. Therefore, the specific fracture mechanical parameters such as fracture energy, characteristic length, uniaxial tensile strength and softening behaviour were determined in order to get a quantitative analysis. The above mentioned parameters are dominantly influenced by compressive strength, modulus of elasticity, uniaxial tensile strength and dry density of the chosen concrete. For that reason altogether 15 different concrete mixtures have been tested with regard to the large scatter of possible lightweight aggregate concretes. The difference in mix design is resulted particularly from the use of several lightweight aggregates. As coarse aggregates expanded clay and expanded slate have been considered. In all cases pozzolanic admixtures and superplasticizers were used to guarantee a sufficient workability and consistency. The softening behaviour after reaching the maximum tensile stresses was determined from a path controlled uniaxial tensile test. For this purpose, an optimised test specimen was developed on the basis of a finite element analysis.

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