# DEVELOPMENT OF A WATERPROOF LIGHTWEIGHT MORTAR FOR SLIM STRUCTURAL ELEMENTS – AS A CONCRETE CANOE

# ENTWICKLUNG EINES WASSERUNDURCHLÄSSIGEN LEICHTMÖRTELS FÜR DÜNNE BAUTEILE – WIE EIN BETONKANU

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## SUMMARY

Concrete is a very versatile material. Particularly in the 1960s and early 1970s, lightweight concrete was successfully used nationally and internationally as an alternative to normal concrete [1]. Afterwards, its importance stagnated until the 1990s. From then on, structural lightweight concrete was increasingly used again, mostly for weight reasons. This was facilitated by recent developments in research and makes lightweight concrete an extremely versatile material today. The problem here, is often its lower water absorption resistance compared to normal concrete. Another application is the construction of a thin-walled concrete canoe, for which a structurally dense lightweight mortar was developed within the scope of this study. The focus was on a low density and a high water absorption resistance of the mortar. For this reason, expanded glass granulate manufactured by Liaver was used as fine lightweight aggregates (LWA). Finally, a solid mortar raw density of 1.60 kg/dm³ with a 28-day compressive strength of 41.7 N/mm² and a bending tensile strength of 7.6 N/mm² could be achieved.

## ZUSAMMENFASSUNG

Beton ist ein sehr vielfältiger Werkstoff. Insbesondere in den 1960er-Jahren und Anfang der 1970er-Jahre wurde Leichtbeton erfolgreich als Alternative zu Normalbeton national und international eingesetzt [1]. Danach stagnierte seine Bedeutung bis in die 1990er-Jahre, von wo an wieder verstärkt auf Konstruktionsleichtbeton, meist aus Gewichtsgründen, zurückgegriffen wurde. Dies wurde durch neuere Entwicklungen in der Forschung begünstigt und macht Leichtbeton

heutzutage zu einem äußerst vielseitigen Werkstoff. Problem hierbei ist jedoch oft sein im Vergleich zu Normalbeton niedrigerer Wasseraufnahmewiderstand. Ein weiteres Einsatzgebiet ist der Bau eines dünnwandigen Betonkanus, wofür im Rahmen dieser Arbeit ein gefügedichter Leichtmörtel entwickelt wurde. Der Fokus dabei lag auf einer geringen Dichte, sowie auf einem hohen Wasseraufnahmewiderstand des Mörtels. Aus diesem Grund wurde Blähglasgranulat der Firma Liaver als feine leichte Gesteinskörnung (LWA) verwendet. Schlussendlich konnte eine Festmörtelrohdichte von 1,60 kg/dm³ bei einer 28-Tage-Druckfestigkeit von 41,7 N/mm² und Biegezugfestigkeit von 7,6 N/mm² erzielt werden.

# 1. INTRODUCTION

The mortar developed here is primarily intended for the construction of a concrete canoe and is to be applied with a trowel (Fig. 1). It should have a low density and still be sufficient strengths. For this a compressive strength of 40.0 N/mm² and a bending tensile strength of 7.0 N/mm² were defined as target strengths.

*(a) as a first layer* *(b) as a second layer on first layer and textile reinforcement*

*Fig. 1: Application of the mortar with a trowel on the outer formwork of a canoe*

Further processing requirements on the mortar, especially for the application on vertical surfaces, are sufficient tack and no tendency to flow.

The composition of the aggregates was calculated using the modified Andreasen model [3]. For this, the particle size distribution of each aggregate was carried out with a classical sieve analysis and in comparison, with a photo-optical particle analysis. Differences found are explained in section 2.1.

Moreover, the water absorption of the lightweight aggregates was determined using the so-called BVK method, see section 2.2.

Fig. 2 shows the basic load-bearing behaviour of lightweight concrete, whereby the failure in lightweight concrete is a failure of the lightweight aggregate in transverse tension.

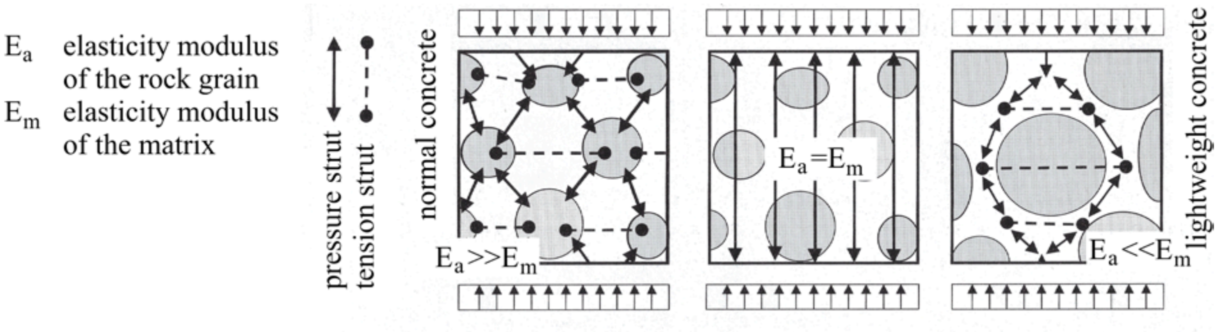


*Fig. 2: Structural model of load transfer in normal and lightweight concrete as well as in a concrete with individual components of equal stiffness [2] (translated)*

# 2. ANALYSIS ON THE RAW MATERIALS

## 2.1 Determination of the particle size distribution

### 2.1.1 Modified Andreasen model

As already mentioned in the introduction, the modified Andreasen model [3] can be used to find a sieve-line based particle composition for the mortar mixture. The mathematical description of the through fraction $A_i$ in vol. % depending on the sieve width $d_i$ is shown in equation (1). Besides the smallest ($D^q_{min}$) and largest ($D^q_{max}$) particle size is considered.

$$A_i = \frac{d_i^q - D^q_{min}}{D^q_{max} - D^q_{min}} \qquad (1)$$

The distribution modulus $q$ is a measure of the distribution width of the particle size distribution and must be selected lower the more the individual particles deviate from an ideal spherical shape [4]. A lowering of the exponent $q$ leads to a higher proportion of fine particle, with the consequence, that the intergranular spaces are filled and the packing density increase. This leads after [5] to higher strength and structural tightness. According to [6], the volumetric water fines value $w/F_V$ is a simplified description of the packing density.

With a distribution modulus optimally adapted to the grain shape, the less dense arrangement of the individual particles due to their less favourable grain shape can be compensated for and an optimally graded particle size distribution can be achieved [7]. For this, as [8] describes, all solid particles contained in the mixture must be included according to their own particle size distribution.

### 2.1.2 Sieve analysis and photo-optical particle analysis

In the preliminary investigation phase, all potentially available aggregates larger than 0.063 mm were investigated by sieve analysis according to DIN EN 933-1 [9]. Afterwards, selected aggregates were analysed with a photo-optical particle analyser (PartAn 3001 L from Microtrac) and the results were compared with those of the sieve analysis (Fig. 3). As expected, the differences are smallest for the almost spherical expanded glass granulate. On the other hand, the deviations are striking in the further graded sands 0/2 and 0.2/2, whose passage was on average 15 vol. % lower when measured with the photo-optical particle analyser.

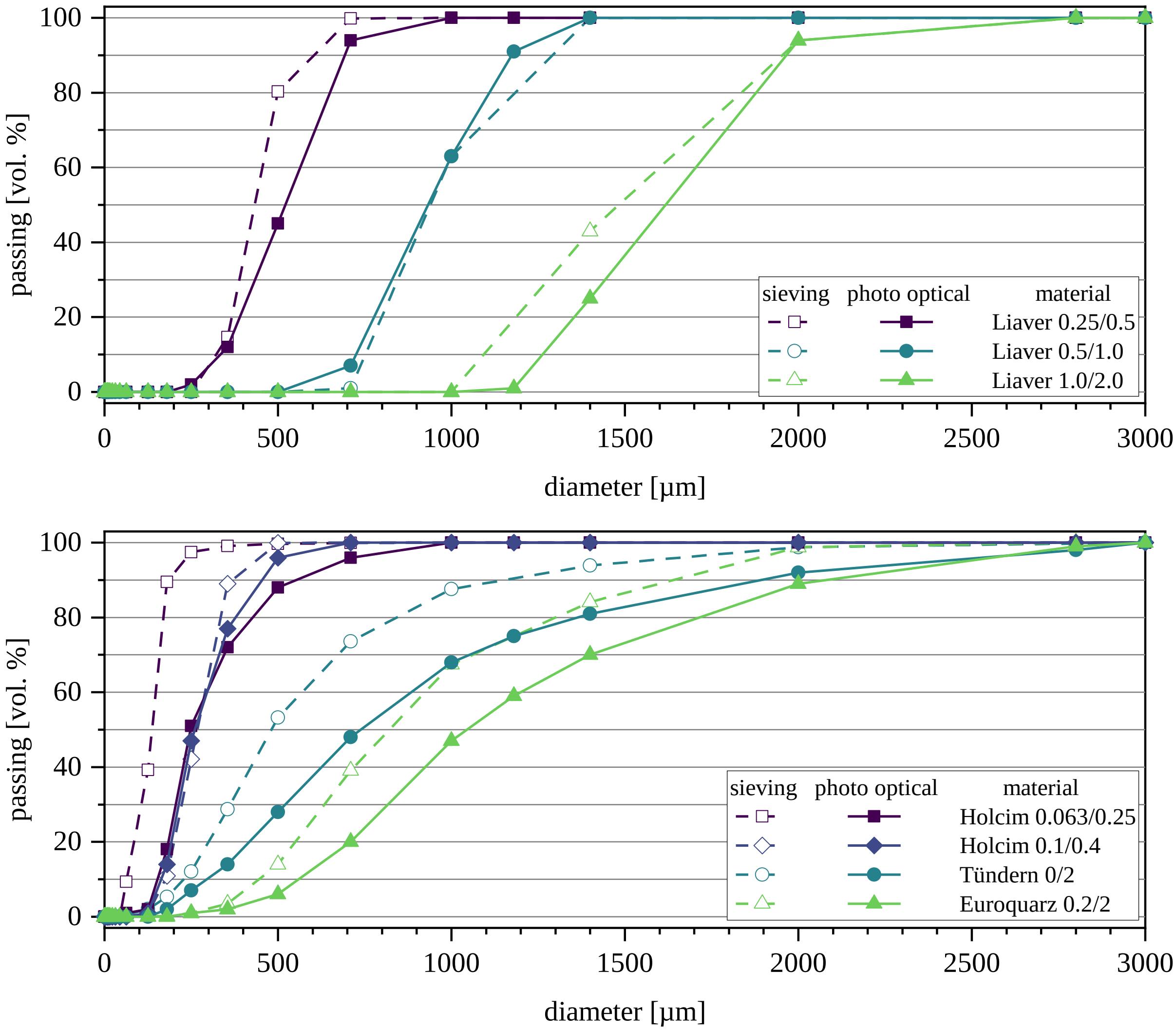


*Fig. 3: Comparison of the results of particle sizing by sieve analysis and photo-optical particle analysis for LWA (above) and sand (below)*

The very clear difference in the sand 0.063/0.25 can be attributed to a high proportion of very platy and very thin particles. They fall through the analysis sieve with their very small width in relation to their length (Fig. 4), but they are detected by the particle analyser in their full particle shape. This results in an accumulation of the measured particle in the larger particle size ranges. Another problem lies in the interpretation of the recorded images by the system. Sometimes two or more particles next to or behind each other are identified as one particle (Fig. 5).

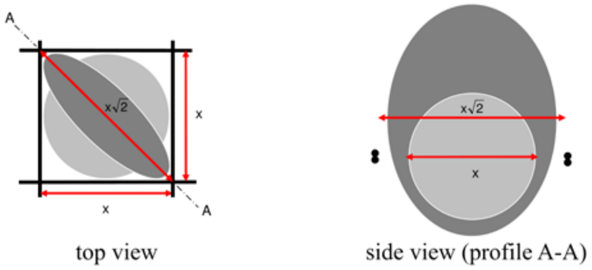


*Fig. 4: Schematic representation of the passage of a spherical and a platy particle through a square hole sieve with opening width x [10] (translated)*

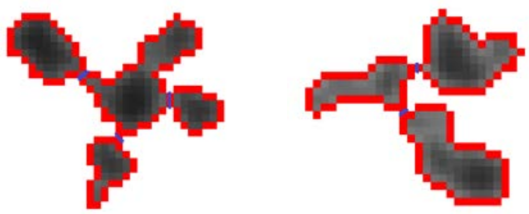

*Fig. 5: Exemplary representation of particles erroneously combined from several individual particles by the software*

## 2.2 Determination of the water absorption of the LWA

In addition to the determination of the particle size distributions of the aggregates, the water absorption of the lightweight aggregates was determined in preparation for the mixture development. The so-called BVK method according to DIN V 18004 section 5.3 [11] was used for this. A vacuum controller was added to the experimental set-up (Fig. 6) to control the negative pressure.

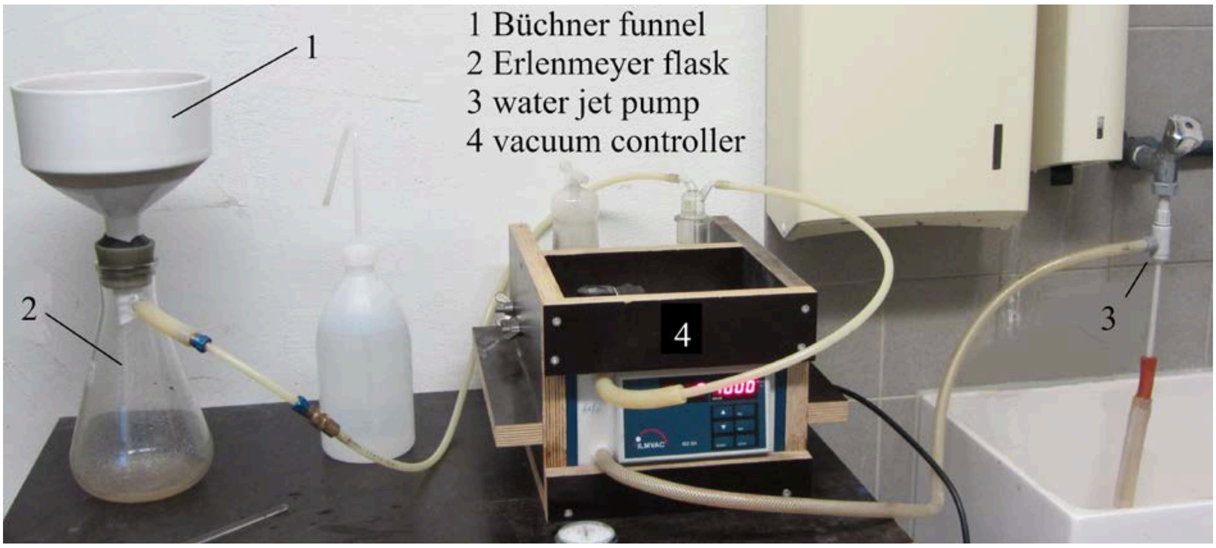


*Fig. 6: Experimental set-up of the BVK method to determine the water absorption of fine lightweight aggregate, supplemented by a vacuum controller*

The expanded glass granulate was tested under ambient air humidity condition and the soaking time was varied from three to ten minutes. In addition, measurements were carried out with 90 mbar relative negative pressure and a whole series of measurements with 70 mbar relative negative pressure. The results found are presented in Fig. 7.

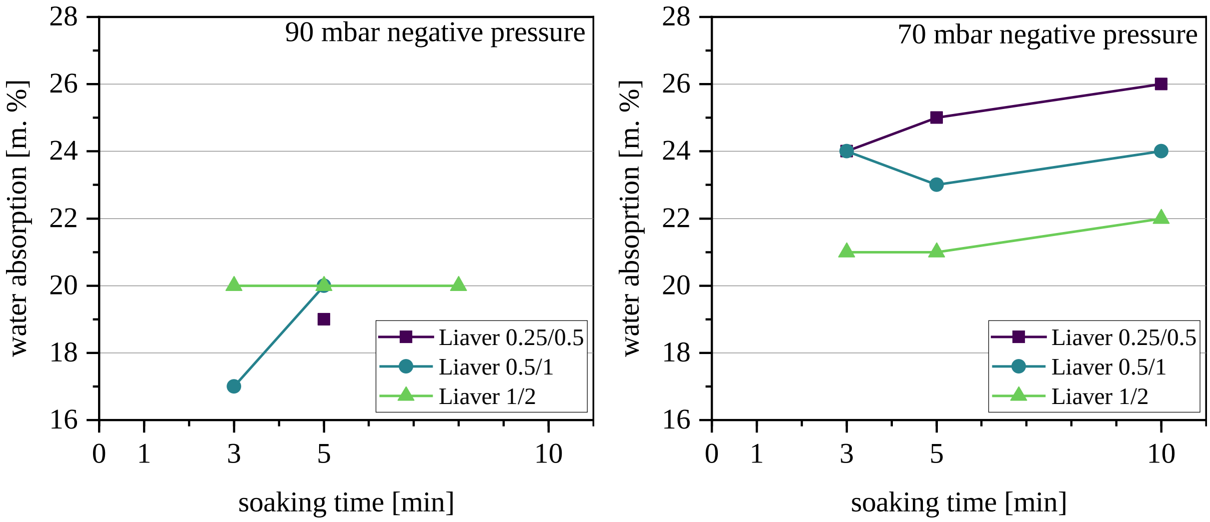


*Fig. 7: Water absorption of the three different grain fractions of the expanded glass granulate with the BVK method in ambient air-dry initial state; left: with 90 mbar negative pressure; right: with 70 mbar negative pressure*

As the two diagrams clearly show, water absorption is higher at lower negative pressure. However, in order to maintain the vacuum range from 50 to 100 mbar specified by the standard, even in the case of control-related pressure fluctuations, 70 mbar relative negative pressure is preferable. Preliminary investigations showed that a value of 90 mbar leads to pressure surges significantly above 100 mbar, especially in the initial period. This explains the significantly lower water absorption. An increase in water absorption with increasing soaking time can be observed, too.

# 3. MORTAR DESIGN

## 3.1 Basic considerations for the mix composition

The aim of the mortar development was a resilient structurally dense lightweight mortar with as few additives as possible.

### 3.1.1 Additional water for the LWA

For the mixing regime, it is intended not to pre-soak the LWA in water, but to add extra water at the beginning of the mixing process. [2] recommends to consider only 70 % of the value of water absorption when designing the mix, because during the test a certain amount of residual water remains on the grain surface and the higher viscosity of the cement paste compared to water would cause the grain pores to clog more quickly. However, since the extra water is to be added in advance, 90 % of the water absorption determined with the BVK method at 5 min soaking time is assumed as additional water of the expanded glass granulate for the mixture calculation.

### 3.1.2 Content of expanded glass granulate and distribution modulus

For a better estimation of the influence of the expanded glass content and the distribution modulus *q* on the strength, different mixtures with a maximum grain size of 2.8 mm were produced.

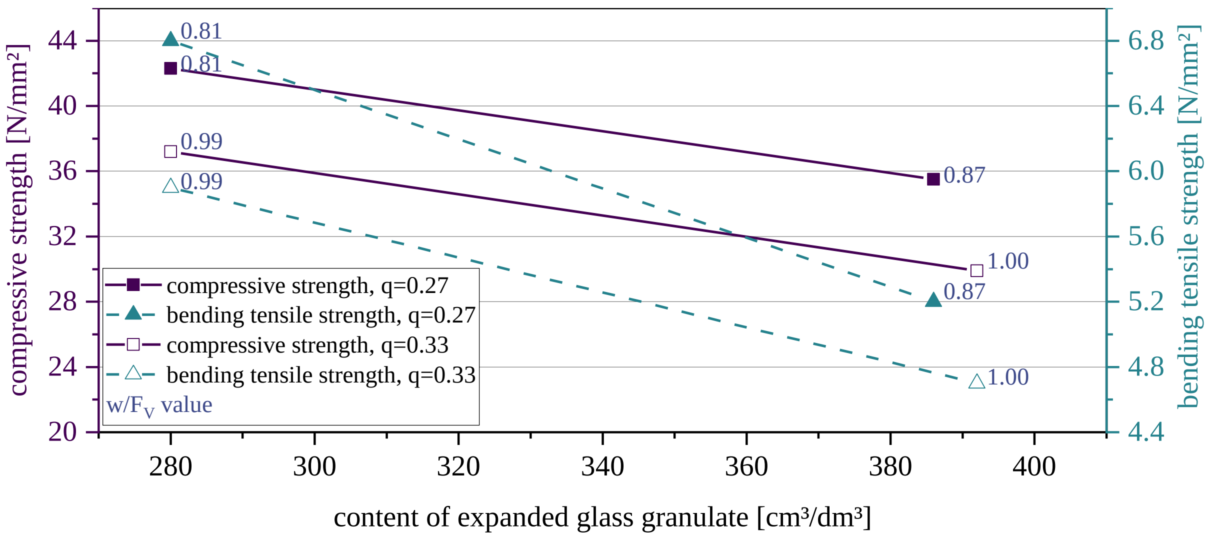


*Fig. 8: Influence of the expanded glass content on the compressive and bending tensile strength, tested on prisms with $(w/c)_{eq} \approx 0.35$ after 7 days*

The results are represented in Fig. 8. The statement of [5] can be confirmed, a lower distribution modulus leads to a lower volumetric water fines value and finally to higher strength with the same w/c ratio.

## 3.2 Mortar admixtures

The positive effect of fly ash, after [2] especially for lightweight concrete, the reduction of hydration heat, is considered insignificant in view of the low wall thickness of 1 cm. Furthermore, these spherical particles with a smooth surface lead to improved flow properties, which is also not desired. Consequently, no fly ash was used.

Starting from a mixture with an expanded glass granulate volume of 280 dm³/m³, three dosages each of silica fume and dispersible polymer powder were added.

### 3.2.1 Influence of silica fume

Silica fume is to be used to improve the fresh mortar properties and to increase the structural tightness. Due to the extremely fine silica fume, the fines content in the mortar increases and consequently the $w/F_V$ value decrease. This leads according to [5] to a lower porosity. [2] was able to observe an improved compaction capability and a smoother surface of the mortar, especially with fine lightweight aggregates.

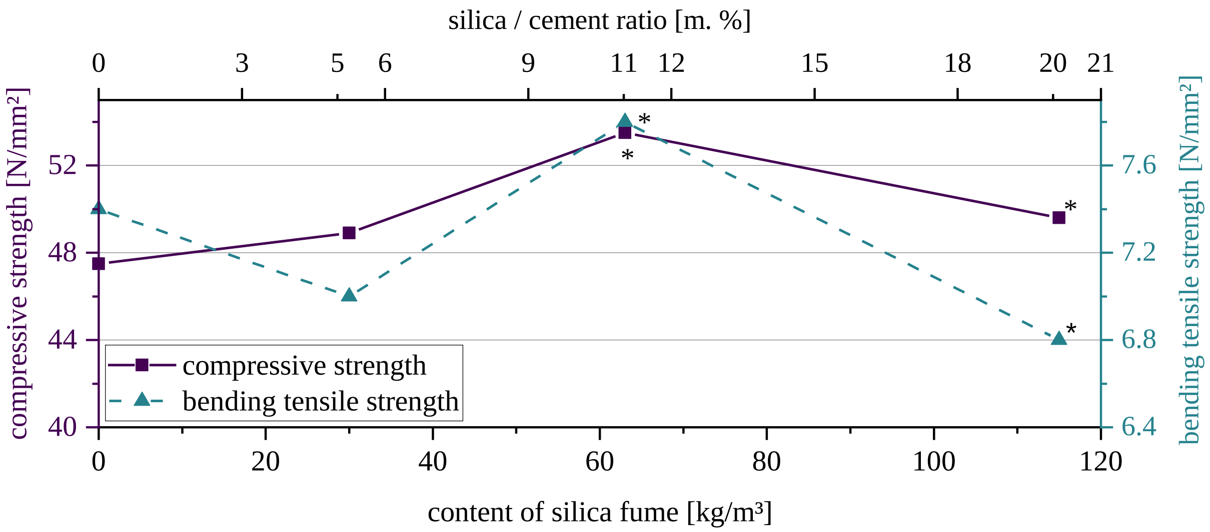


*Fig. 9: Influence of the silica fume content on the compressive and bending tensile strength, tested on prisms with an expanded glass granulate content of 255 - 280 cm³/dm³ after 7 days resp. (*) after 8 days*

In the trials, the results are shown in Fig. 9, leads a higher content of silica fume until 11 m. % of cement to higher strength. This ratio represents the maximum permissible addition quantity according to the manufacturing specifications. Beyond this, a decrease in strength can be observed. This is in line with the standard silica fume content of 10 % given by [12] for high-strength lightweight concretes.

### *3.2.2 Influence of dispersible polymer powder*

Cement mortar with added plastic, also known as Polymer Cement Concrete (PCC), have a joint binder effect between cement and polymer if the polymer in the structure of the PCC actually forms an adhesive bond with the inorganic particles. Although a reduced compressive strength is to be expected, the bending strength is increased in this state. The latter is due to the so-called crack stopper function (Fig. 10). If there are sufficient polymer particles in the mortar due to dispersion, microcrack development can be reduced by the polymer requiring additional energy to open a crack. If this influence is greater than the reduction in tensile strength due to the lower elastic modulus because of the polymer particles, an increased (bending) tensile strength can be expected [13]. This is desirable because the bending tensile strength is more decisive than the compressive strength.

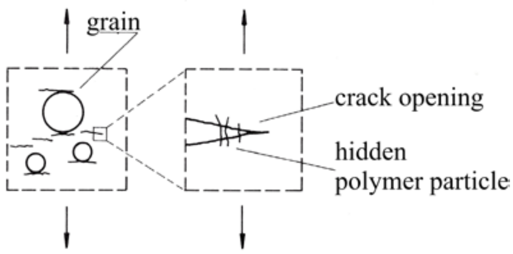


*Fig. 10: Illustration of the crack stopper function [13] (translated)*

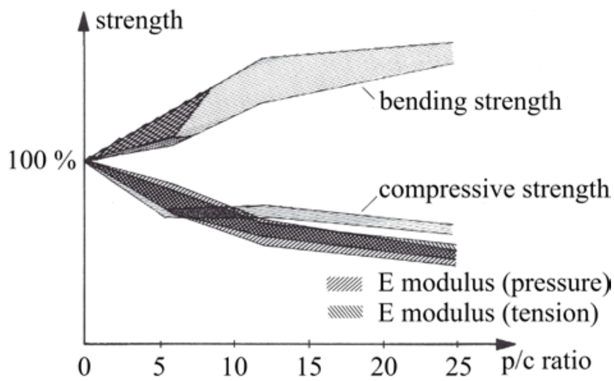


*Fig. 11: Typical property profile of a PCC [13] (translated)*

Consequently, analogous to the silica fume, the dispersible polymer powder was also added in three dosage levels. The measured strengths are displayed in Fig. 12.

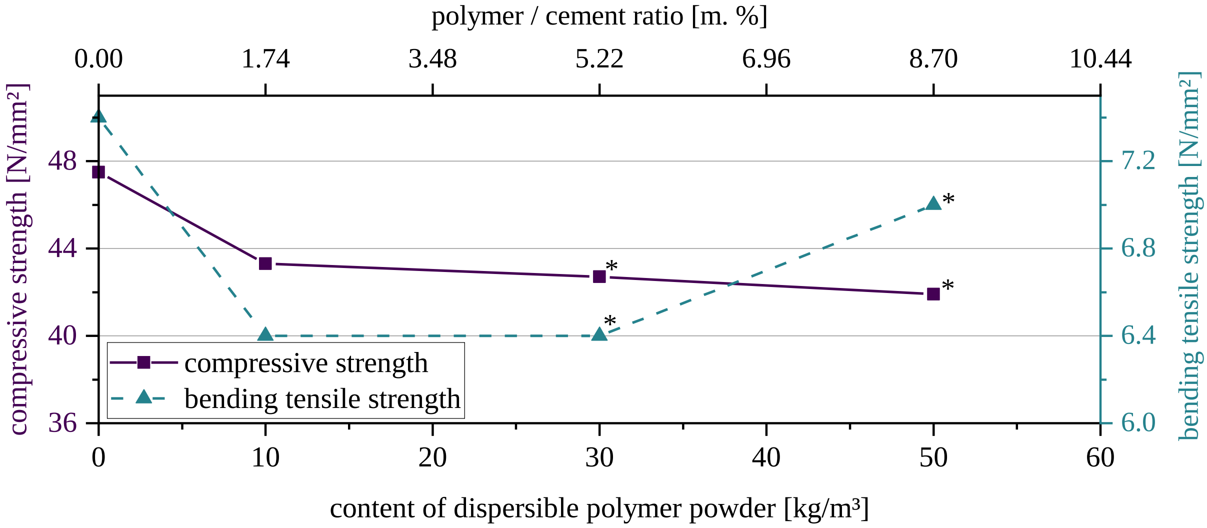


*Fig. 12: Influence of the dispersible polymer powder content on the compressive and bending tensile strength, tested on prisms with an expanded glass content of 255 - 280 cm³/dm³ after 7 days resp. (*) after 8 days*

Comparing the strengths achieved with those in Fig. 11, we see that there was no increase in bending tensile strength. Consequently, it must be assumed that the polymer content is too low to compensate the strength-reducing influence of the polymer particle by an increased crack opening energy. The liquefying effect of the dispersible polymer powder, as [14] describes it, could be confirmed by a strong increase in the slump of the mortar. This is also the reason why only an addition of 3 m. % of cement was pursued.

### 3.3 Improvement of the fresh mortar properties

An important aspect is the increase of the yield point of the mortar. For this purpose, the highly effective powdered PCE-superplasticizer was replaced by a liquid plasticizer based on melamine/naphthalene sulphonate. The extremely pronounced steric effect of the PCE-superplasticizer leads to a strong reduction of the yield point, which is not to be used in case of mortar application on vertical surfaces. In contrast, the newly used plasticiser belongs to the group of polycondensates, which are not as effective, but do not cause a lowering of the yield point [15]. Fresh mortar tests showed that even a high addition of methyl hydroxyethyl cellulose could not completely compensate the yield point reducing effect of the PCE-superplasticizer. Accordingly, the new plasticizer was used, with the consequence that the w/c ratio had to be raised slightly to 0.40 to be able to guarantee sufficient effectiveness. The associated decrease in strength was attempted to be compensated for by lowering the $w/F_V$ value. This in turn was implemented by reducing the distribution modulus $q$ from equation (1) from the originally envisaged 0.28 - 0.32 to 0.25. For a representation of the total particle size distribution of the final mixture compared to this target sieve line (modified Andreasen model with $q = 0.25$), see Fig. 15.

Another aspect is the maintenance of mortar consistency over the time of installation. A methyl hydroxyethyl cellulose (MHEC) is used for this purpose. It acts as a thickener agent and at the same time as a water retention agent. This makes certain changes in the mixing regime necessary. For example, the MHEC should be given a certain resting period after the main mixing, to be able to develop a better effect. This leads to the mixing regime shown in Fig. 13. A standard mortar mixer according to DIN EN 196-1 [16] was used.

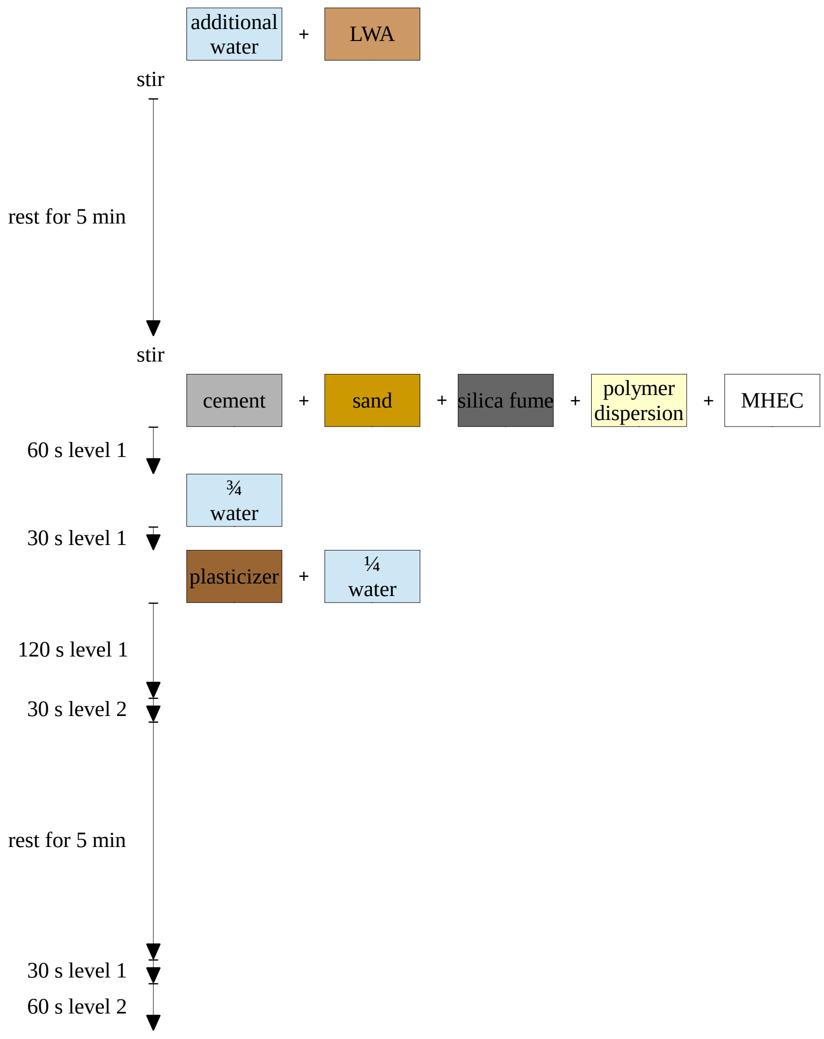


*Fig. 13: Graphical representation of the final mixing regime*

## 3.4 Finale mixture

### 3.4.1 Composition

Based on the above findings, the following mixture was developed. The expanded glass granulate content was targeted at approximately 250 cm³/dm³ to achieve sufficiently high strengths, compare Fig. 8. Table 1 gives a short overview of the composition of the mortar and its important properties. A deeper look on the characteristic values, especially the strength, can be found in the following section 3.4.2.

*Table 1: Mortar composition and properties of the finale mixture*

| CHARACTERISITC MATERIAL | UNIT | FINALE MORTAR MIXTURE |
|---|---|---|
| Cement | | Holcim CEM I 52.5 R-SR 3 (na) |
| content | kg/m³ | 575 |
| Adding water | kg/m³ | 239 |
| Additional water | kg/m³ | 26 |
| $(w/c)_{eq, total}$ ratio | | 0.44 |
| $(w/c)_{eq, eff}$ ratio | | 0.40 |
| $w/F_V$ ratio | | 0.87 |
| Aggregates | | |
| Quarzwerke 0/0.063 | kg/m³ | 153 |
| Holcim 0/0.063/0.25 | kg/m³ | 331 |
| Holcim 0/1 oÜK | kg/m³ | 153 |
| Lightweight Aggregats | dm³/m³ | 241 |
| Liaver 0.25/0.5 | kg/m³ | 52 |
| Liaver 0.5/1 | kg/m³ | 65 |
| Concrete admixtures | | |
| silica fume | | Sika Silicoll P |
| content | m. % of c. | 10.0 |
| Dispersible polymer powder | | Wacker VINNAPAS 5044 N (GER) |
| content | m. % of c. | 3.0 |
| Plasticizer | | Sika FM6 |
| content | m. % of c. | 2.50 |
| Methyl cellulose | | SE Tylose MH 60006 P6 |
| content | m. % of c. | 0.05 |
| Fresh mortar | | |
| Density | kg/dm³ | 1.60 |
| Concrete spread acc. to DIN EN 1015-3 | cm | 12.1 |
| Air void content | vol. % | 12.5 |
| Hardened mortar | | |
| Density | kg/dm³ | 1.60 |
| Compressive strength after 7d / 28d *) | N/mm² | 34.1 / 41.7 |
| Bending tensile strength after 7d / 28d *) | N/mm² | 5.7 / 7.6 |
| *) on mortar prims | | |

### 3.4.2 Characteristic values

After one day at 20 °C / 95 % r.h. in the formwork, the prisms were stored for further 6 days under the same climatic conditions before they have been stored under 20 °C / 65 % r.h. until the 28th day. The development of both strengths over time is shown in Fig. 14. Consequently, the target strengths were achieved with a compressive strength of 41.7 N/mm² and a bending tensile strength of 7.6 N/mm².

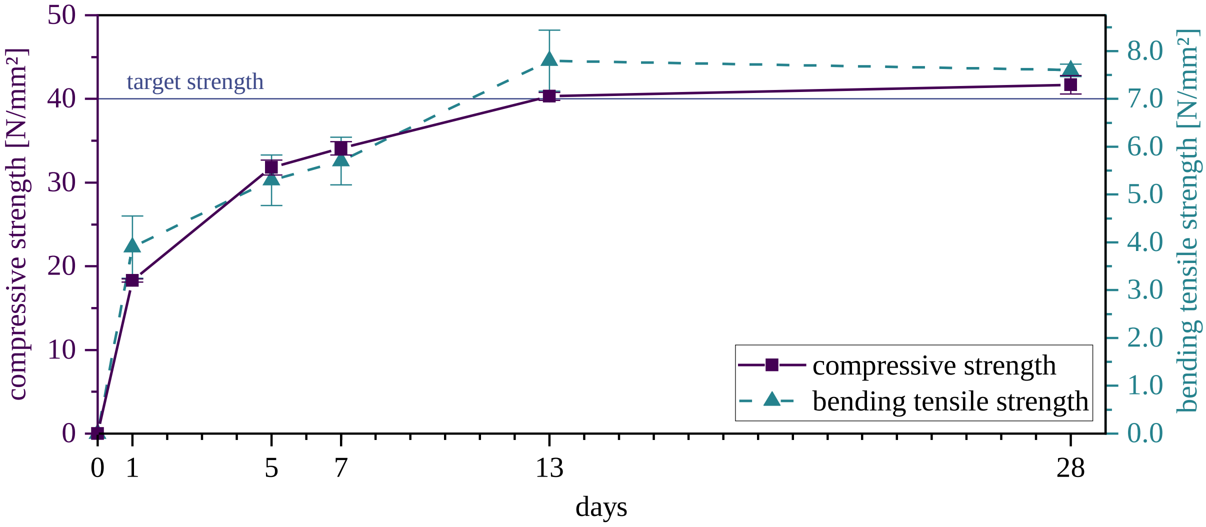


*Fig. 14: Development of compressive and bending tensile strength of mortar prisms over time*

The particle size distribution of all solid particles contained in the mixture is shown in Fig. 15. Fig. 16 also gives a photograph of the fracture surface of a mortar prism after the bending tensile test.

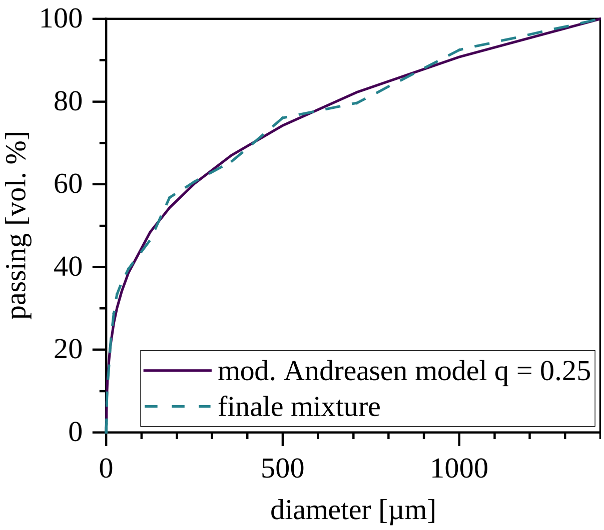


*Fig. 15: Representation of the total particle size distribution of the final mixture compared to the target sieve line*

*Fig. 16: Photograph of the fracture surface of a prism after bending tensile test*

# 4. CONCLUSION AND OUTLOOK

It was possible to develop a structurally dense lightweight mortar with Liaver expanded glass granulate, which has a density of 1.60 kg/dm³, as well as a compressive strength of 40 N/mm² and a bending tensile strength of 7.5 N/mm². Compared to the usual solid mortar densities of 2.30 to 2.40 kg/dm³, this means a reduction of 30 %. Converted to the weight of a usual concrete canoe, for which this mortar will mainly be used, this means a weight saving of around 40 kg per boat.

To test the water absorption under real conditions, a half-shell with a diameter of 15 cm was made and left to float in a water basin, whereby a water absorption of 0.1 m. % could be measured.

A possible improvement of the mortar composition is to increase the proportion of dispersible polymer powder, cf. Fig. 12, as at present only a liquefying effect occurs, whereby reduced strengths must be accepted at the same time. With this measure, the structure type c according to [13] can be achieved, which means a closed polymer phase and increased bending tensile strength. The resulting change in mortar consistency must be counteracted by appropriate measures.

Furthermore, the mixture developed here must be transferred to a correspondingly larger mixer for later use, whereby a change in consistency must be considered if necessary. For this, the concreting of a test canoe is recommended.

A further development step is the topic of reinforcement, which must be seen in connection with the overall load-bearing behaviour of mortar and reinforcement. This raises the question of the type of reinforcement, e.g. fibres (textile or carbon) or steel wire, but also its specification. It must be able to guarantee ductile load-bearing behaviour and the best possible crack prevention.

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