A MODEL FOR THE PREDICTION OF THE MATERIAL ATTRIBUTES OF HYBRID HIGH STRENGTH CONCRETE

EIN MODELL ZUR VORHERSAGE DER METERIAL EIGENSCHAFTEN HOCHFESTER HYBRIDBETONE

UN MODÈLE POUR LA PRÉDICTION DES PROPRIÉTÉS DES BÉTONS AVEC BÉNIN GRANULAT SATURÉ

Christian Piehl, Sven Mönnig

SUMMARY

This article is based on the work and results of a diploma thesis. The ambition was to model and predict the influence of presaturated lightweight aggregates (LWA) on high strength concrete. The model is based on the results of a research program and was validated by values published in literature.

ZUSAMMENFASSUNG

Dieser Artikel präsentiert die Arbeiten und Ergebnisse einer Diplomarbeit, die sich zum Ziel gesetzt hatte, ein Modell zur Beschreibung und Vorhersage des Einflusses von vorgesättigten Leichtzuschlägen (LWA) auf hochfesten Beton zu erstellen. Das Modell wurde basierend auf einer Versuchsreihe aufgestellt und an unabhängigen Werten validiert.

RESUME

L’article présent la travaille d’un mémoire. La motivation a été la réalisation d’un modèle pour béton avec bénin granulat saturé. Le modèle est fondé aux résultats des expériences et a été révisé avec résultats publiés.

KEYWORDS: model, lightweight aggregates, high-strength concrete

1 INTRODUCTION

The influence of internal water storage systems based on water saturated lightweight aggregates was thoroughly investigated by different researchers in the past [1],[2],[3],[4]. The measurements of Reinhardt and Beckert [4] showed that the results are not only dependent on the concrete mixture but also on the material attributes of the lightweight aggregates. The ambition of this research work was the determination and quantification of the important material attributes and the derivation of coherences and equations to model the compressive strength of hybrid concretes. The paper presents in its first part the results of the laboratory work. It was found that the compressive strength of a hybrid concrete decreased with the LWA content after 28 days. However, after 56 days the compressive strength increased significantly. The hydration was apparently elongated by the water stored by the LWAs. The results show that the degree of saturation has a strong influence on the effectiveness of internal curing. The second part of the paper presents models that are able to predict the compressive and tensile strength development with reasonable accuracy, even for not completely saturated LWAs.

2 LABORATORY RESULTS - MATERIALS AND METHODS

2.1 Materials

The cement used was a CEM I 42.5 R type. Its Bogue phase composition was C_3S: 61.0 %, C_2S: 8.6 %, C_3A: 9.1 % and $C_4(AF)$: 8.9 %. The Blaine fineness was determined to be 4180 cm^2/g. The density was 3.15 kg/dm^3. Rhine gravel was used as aggregate with a density of 2.61 kg/dm^3. The aggregates had a medium compressive strength of about 80 to 100 MPa. Polycarboxylatether, Woerment FM 375, was used as superplasticizer. It had a density of 1.08 kg/dm^3.

The lightweight aggregates were made of expanded clay (Liapor F9.5) produced by Liapor. The grains had a medium diameter of approximately 5 mm and a density of 1.7 kg/dm^3. Table 1 shows the absorption capacity and compressive strength of the LWAs. The aggregates consist of a relatively dense sinter skin and a rather porous core. The water delivery rate is mainly dependent of the pore size of the outer sinter skin while the total storage capacity depends on the porosity of the core. During hydration reaction products can narrow the pores and slow down the water delivery. This process results in slow water desorption and long lasting curing of the paste. In contrast the absorption of water happens very fast. The LWA reached 50 % of the 24 hours water absorption after an average of 22 minutes.

Table 1: Used LWA Liapor F9.5

Type	Size Range [mm]	Compressive Strength [1] [MPa]	Gross Density [kg/m^3]	Water Absorption [2] 24 h [% by mass]
F9.5	< 4	17	1700	19.0
	4 < d < 6.3			16.1
	> 6.3			15.7

[1] Information was given by Liapor [2] Including surface moisture

2.2 Mixtures

The mixtures had a lightweight aggregate volume content that was varying between 10 and 30 % of the total concrete volume. Table 2 shows the investigated mixtures. For each mixture the LWAs were added in three different conditions: dry (d), 50 % saturated – half saturation (hs) and saturated (s). Saturation was defined as the water absorption after 24 hours. The average water absorption was determined to be 12 % by mass. Due to the surface water of the LWAs a difference of about 4 to 8 % by mass, dependent on the LWA size, compared to values published in literature and in Table 1 was measured. The surface water was subtracted from the mixing water. A total of 10 different mixtures was produced and tested.

Table 2: Examined mixtures

Name	Cement [kg/m^3]	Water [kg/m^3]	Fine Agg. [kg/m^3]	Coarse Agg. [kg/m^3]	Super-plasticizer [kg/m^3]	LWA [kg/m^3]
Reference	458	161	812	998	3.4	0
10(d,hs,s)	456	161	809	728	3.4	175
20(d,hs,s)	456	161	782	490	2.8	346
30(d,hs,s)	456	161	779	226	4.5	517

2.3 Experimental procedure

The necessary quantity of superplasticizer was determined by preliminary tests. The cement and the aggregates were homogenised for half a minute.

Afterwards 2/3 of the water was added and the concrete was mixed for another minute. Afterwards the remaining water was added together with the superplasticizer and the blend was mixed for another 1.5 minutes. The moulds were cast and vibrated for at least one minute. The vibration time was extended until no visible air bubbles were emerging anymore. A total of 18 cubes, $10 \cdot 10 \cdot 10$ cm^3, and one cylinder, diameter 15 and height 30 cm, were cast for each mixture. The cubes were used to determine the splitting tensile and the compressive strength after 28 and 56 days. The paper presents values that are an average of three individually tested cubes. The cylinder was used to measure the dynamically tested Young's modulus. After 24 hours the specimens were demoulded and stored at 20°C and 100% RH for another 6 days. After this period they were stored at 20°C and 65% RH.

3 RESULTS

Figures 1, 2 and 3 show the results of the measurements. The grey indicated back ground colour represents the 56 days values, except for mixture 10-s where only 28 days values were determined. The hatched columns, mixtures 20-d and 30-d, indicate that the 56 days values were smaller than the ones measured after 28 days but the decrease in strength was smaller than the standard deviation.

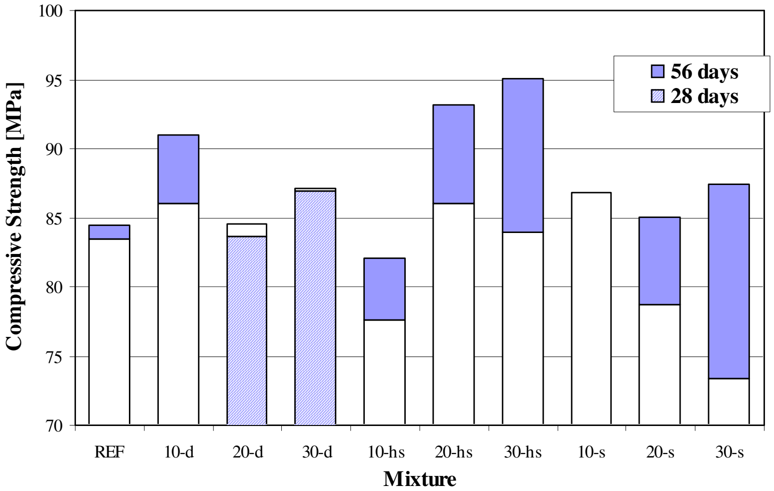

Figure 1: Compressive strength values measured after 28 and 56 days.

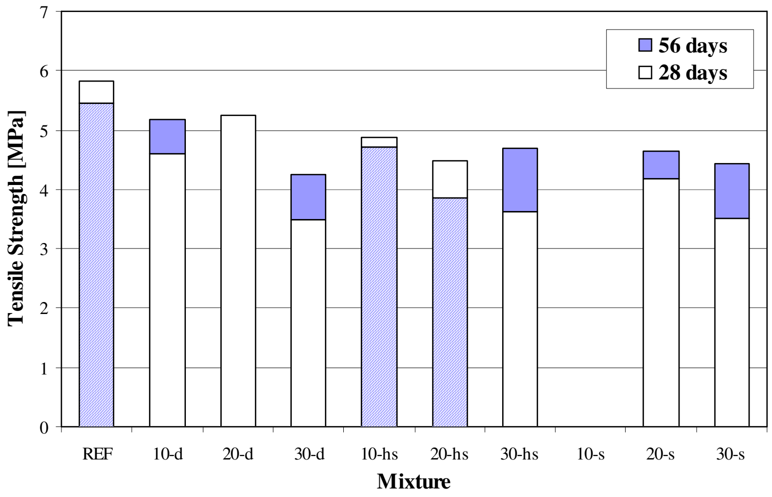

Figure 2: Splitting tensile strength values measured after 28 and 56 days

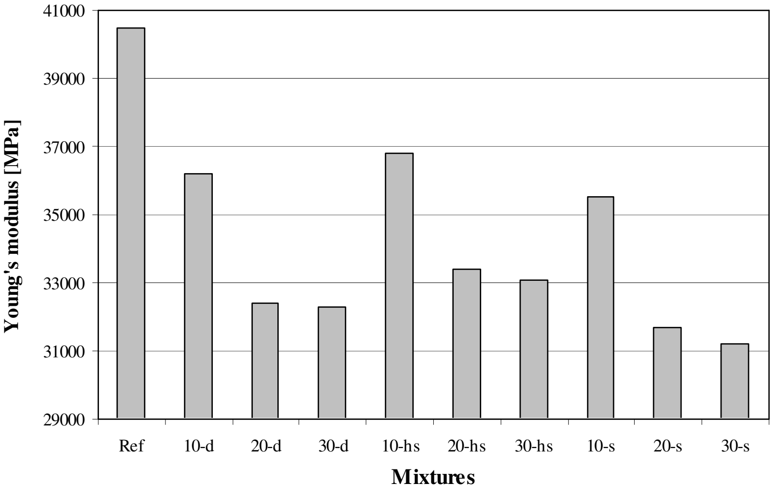

Figure 3: Young's modulus measured after 28 days

4 DISCUSSION OF THE RESULTS

The compressive strength development was different for all mixtures. The changes were dependent on the degree of saturation and the LWA content. The dryly added LWA showed little influence. They neither increased nor decreased the compressive strength for the mixtures 20-d and 30-d. The mixture with a volume content of 10 % had a higher compressive strength after 56 days. The results of the compressive strength tests show a significant increase of the strength for the mixture with fully saturated LWAs between the 28th and the 56th day. For the half saturated mixtures this effect was also measurable. Table 3 presents the strength increase.

Table 3: Increase of the compressive strength between the 28th and the 56th day

Mixture	Increase [MPa]	Percentages Increase [%]
REF	1	1.9
10-d	4.96	5.76
20-d	-0.85	-1.01
30-d	-0.16	-0.19
10-hs	4.51	5.81
20-hs	7.07	8.21
30-hs	11.12	13.24
20-s	6.35	8.06
30-s	14.05	19.15

For the tensile strength development no comparable effect was measurable. The strength increases and decreases were within the standard deviations of the measurements.

5 MODEL

The principle ideas of the model were introduced in [6]. The following subsections specify the model and show the results of the compressive strength simulations. Based on the compressive strength other material attributes can be derived. The paper will show the calculation for the tensile strength and elastic modulus. To model the compressive strength of concrete it is necessary to consider numerous influences which are simultaneously interacting. The model attempts to consider the most important physical influences, i.e. degree of hydration, porosity, type and content of LWA, degree of saturation, tensile strength of the LWAs and the mixture composition of the concrete. The following sub-chapters will explain the individual components of the model in detail. Subsequently the results of a variety of different mixtures, that were used to validate the models, i.e. Piehl [7], Beckert [4] and Zhang [8], will be presented. The mixtures clearly differed. Different types of lightweight aggregates were used, i.e. F9.5, F8 and F6.5. They were differing in size and strength. The LWA volume content ranged from 10 to 35 %. Some mixtures contained silica fume, others did not. The results will show that the model can simulate the different mixtures with good accuracy.

5. 1 Influence of the degree of hydration and porosity - α, ϕ

The degree of hydration is the governing parameter of the model. The amount of water delivered from the LWA to the matrix and the porosity development are dependent on it. The degree of hydration itself can be calculated based on the relative humidity and the temperature. This can be done for example by a program like DuCOM [9]. The results presented within this paper were calculated based on the maximum degree of hydration for each mixture. The maturity was calculated by the Powers model [10]. Two assumptions were made: First, the initial w/c-ratio, without internally stored water, will be sufficient to reach a certain maturity after 28 days. Second, the internally stored water causes an additional hydration of the remaining cement after 28 days. The degrees of hydration were varying between 0.86 for the mixtures without silica fume and 0.77 for the mixtures with silica fume content. Dependent on the degree of saturation and the LWA content most of the cured mixtures should have been able to reach complete hydration. The calculations of the model are based on the assumption of a sealed system, i.e. water loss by evaporation is inhibited. Based on the Bal'sin equation [11] the coefficient n was introduced to revalue the influence of the porosity but for all calculations the factor was set to be equal to one. The model considered capillary pores only.

5.2 Influence of the stored water, degree of saturation S, LWA size and porosity - ΔLS, CV

The curing water content can easily be estimated by the knowledge of LWA particle size distribution, total mixture content and degree of saturation. However, it is also necessary to distinguish the different types of stored water. LWAs can store water in four different ways: core-, surface close- and surface water, or in a combination of some or all of them. Figure 4 shows the water distribution within a LWA. The mesh size symbolizes the particle density.

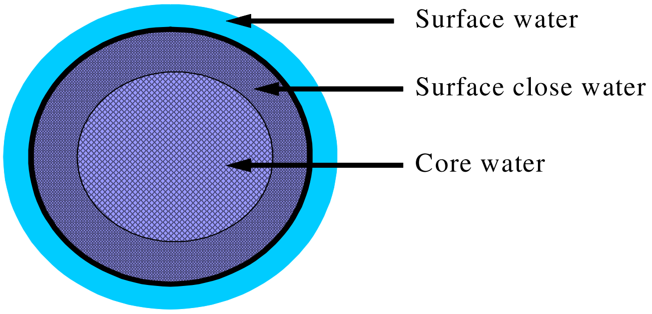

Figure 4: Water distribution within and close to a LWA

Surface water will be emitted during the handling of the aggregates and the mixing of the fresh concrete. This water can be considered to be not available for internal curing since it is delivered at an early stage to the cement paste. Thus the amount of surface water was considered to be part of the mixing water. The surface close water can be easily delivered to the paste, however it prohibits additional moisture uptake of the aggregate during mixing. If the aggregate was only partly saturated, the core of a dry LWA will remain unsaturated. The water will be stored close to the surface. It will be exposed to a driving potential towards the cement paste and into the LWA core, which will reduce the amount of water available for internal curing because part of the water, dependent on the degree of saturation, might be transported into the particle. The core water might be available at later stages of hydration. Capillary suction and diffusion will empty the LWA gradually during hydration. Based on the assumption that the water transport from the grain to the paste starts after either capillary suction or diffusion takes place, it is likely that the desorption will start at later stages of hydration. Thus it is possible to calculate the maximum degree of hydration which is reachable by the mixing water, i.e. without the stored water. The volume content of not hydrated cement, chemical shrinkage and capillary porosity are calculated based on the degree of hydration. At later stage of hydration the additional available water will increase the final degree of hydration and decrease the not hydrated cement content and the capillary porosity. The model takes these effects into account. The strength increase due to internal curing water can be considered to be caused by different influences:

- Increase of the degree of hydration
- Decrease of porosity
- Reduction of stresses and microcracks due to shrinkage, i.e. chemical and autogeneous shrinkage
- Moisture content of the paste, as Jensen reported [12]

The curing water will increase the cement paste content. Based on this assumption the increase of the degree of hydration and the decrease of porosity can be calculated. However, this assumption would only be accurate enough if the size of LWA particles would be comparable to the size of the replaced normal aggregates but the LWA particles have an average size of approximately 4 to 6 mm and the normal weight aggregates ranged between 0.125 and 16 mm. Thus the accuracy increases by calculating the increase of the paste layer thickness, which is covering the aggregates, instead of the increase of the paste volume. The increase of paste layer thickness can be easily calculated based on the particle size distribution and the paste content. De Larrard showed that the paste layer thickness can be correlated to the compressive strength of normal strength concrete [13]. Figure 5 shows that the increase of paste layer thickness has also a good correlation with the strength increase of hybrid concretes.

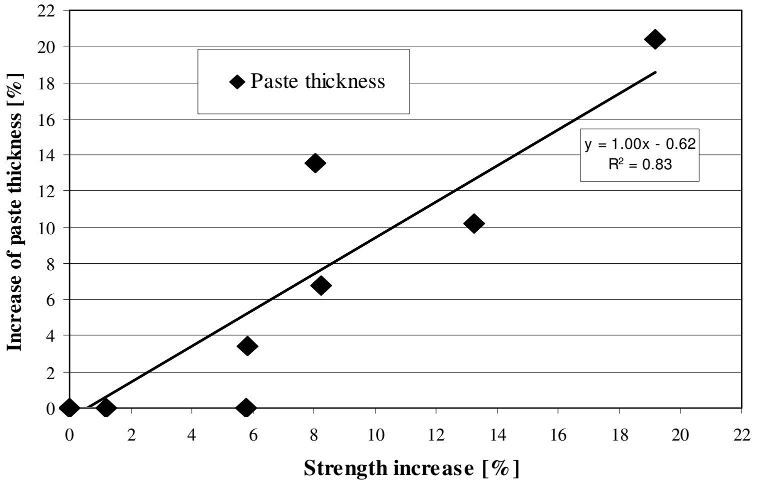

Figure 5: Correlation between compressive strength and paste layer thickness increase

The concrete volume, that presaturated LWAs cures, can be estimated by calculating the amount of water needed to fill the capillary pores resulting from chemical shrinkage. The availability of water is dependent of the lightweight aggregate size and its particle size distribution. Chemical shrinkage can be calculated based on Powers model [10]. The distances where sufficient water is present to circumvent chemical shrinkage ranges between 0.4 and 2 mm, dependent on the LWA size and saturation. Lura measured a water transport distance of about 1 mm from the LWA to the paste [4]. Bentz and Snyder measured an average water transport distance of about 200 µm for lightweight sands [15]. Thus, the calculated values are within the range of measured ones. However, this approach is limited by the total paste volume. The internal curing water can not cure more paste than present. Thus the radius of influence must be reduced by a limiting factor (CV) whose value is dependent on the total paste volume. If the quotient of cured to curable volume is larger than 1 the paste layer thickness will be divided by a factor CV. CV is equal to this proportion.

5.3 Influence of aggregate tensile strength and content – f_{LWA}, P_{LWA}

Faust reported that a correlation between LWA content and compressive strength exists [14]. Beckert [4] also found a decrease of the compressive strength after 28 days dependent on the LWA content. Other authors reported that they did not find any relationship between strength and LWA content [4]. The results of this work show a likewise contradictory pattern. For fully saturated aggregates a decrease of strength was measurable. For dryly added aggregates no decrease was found and the results for the mixtures with half saturated aggregates were inconsistent. Thus it is likely that different influences are simultaneously interacting. On the one hand, the strength and the elastic modulus of the lightweight aggregates are generally smaller than the ones of the paste. On the other hand, the hydration products (CSH) can grow into the LWA hull, forming a strong bond. However, the mismatch of the elastic moduli will cause high stresses within the transition zone causing the splitting of the LWA and the failure of the cube. Based on these assumptions the strength of the composite should be dependent of the strength of the mixture without LWA, the LWA content and the material attributes of the LWAs. The extent of the spurious effect of the LWAs will be dependent on their size and volume content, since both values determine the extent of the weakening of the concrete matrix. To consider the effect of the degree of saturation the coefficient C_{LWA} was introduced. It reduces the effect of the matrix weakening. By introducing a negative paste layer thickness a similar effect would have been reached. This coefficient or the negative paste layer thickness should simulate the absorption of mixing water by the not completely saturated aggregates. Figure 6 shows the values for C_{LWA} as a function of the LWA content.

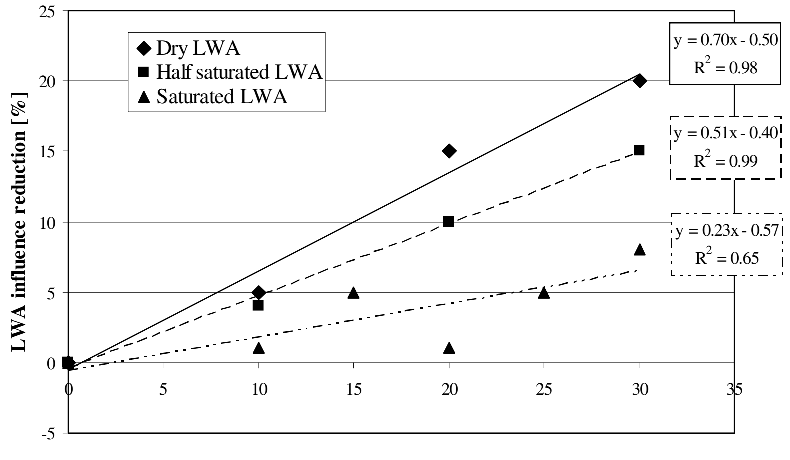

Figure 6: Influence of the coefficient C_{LWA}

The coefficient has a bigger slope for dry aggregates, while the half saturated function is almost in the middle of the line for saturated and dry aggregates.

5.4 Final model and Results

Based on the presented assumptions the final equation can be derived:

$$f_c^{LWA}(\alpha) = f_c^{REF} \cdot \underbrace{(1-\phi)^n \cdot \alpha}_{\text{maturity, porosity}} \cdot \underbrace{(1+\frac{\alpha \cdot \Delta LS}{CV})}_{\text{paste thickness}} \cdot \underbrace{\left(\frac{(f_{LWA} \cdot P_{LWA}) \cdot (f_{NWA} \cdot P_{NWA})}{f_{NWA}}\right) \cdot \frac{1}{(1-C_{LWA})}}_{\text{LWA conten t and tensile strength}} \qquad (1)$$

f_c^M: Compressive strength of the reference mixture; α: Degree of hydration; ϕ: Capillary porosity; n: Coefficient; ΔLS: Increase of paste layer thickness due to curing water; CV: Curing volume, i.e. volume where chemical shrinkage is prevented, f : tensile strength of LWA and NWA, P: volume content of LWA and NWA, C: Correction due to degree of saturation of LWA.

The compressive strength of the reference mixture was measured. The other parameters were calculated based on the given information about the aggregates. Piehl [7] measured an average reference compressive strength of 105 MPa. Beckert [4] found a compressive strength of 140 MPa. The difference can be explained by the high amount of silica fume that Beckert's mixture contained. The presence of silica fume will have two significant influences on the equation: First, the strength of the reference mixture will increase. Second, the chemical shrinkage will also be increased and the final degree of hydration will decrease. The model considers these influences by calculating chemical shrinkage, degree of hydration and a reduced paste layer thickness. Figure 7 presents the results of the model and compares them to the measured ones.

The shape of the symbols represents the amount of LWA added to the mixtures. The colour indicates the degree of saturation and the size the age of the specimens. The first letter symbolizes the used publication. The first number shows the volume content of lightweight aggregates. The colour of the symbols indicates the degree of saturation, i.e. d-white, hs-grey, and s-black. The size of the symbols represents the age of the specimens, i.e. 28 and 56 days.

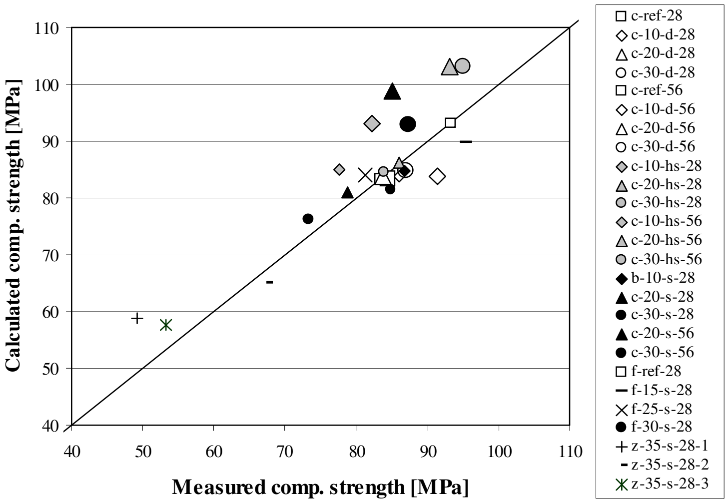

Figure 7: Results of the compressive strength simulation

The agreement of measured to calculated values is very good for the 28 days values. For most mixtures the variation is less than 10 percent. The values measured after 56 days were smaller than the calculated ones. An explanation might be that for the calculated results complete hydration was assumed. This will overestimate the compressive strength and would more likely refer to values measured after 360 days. The stability index of the model, including the 56 days values, was 0.77. Without the 56 days values the index would have been 0.93.

6 TENSILE STRENGTH

The tensile strength can be derived from the compressive strength value because a correlation between compressive strength and tensile strength exists. The tensile strength f_t can be calculated based on the compressive strength f_c according to equation 2.

$$f_{tensile} = k \cdot f_{comp.}^{\;2/3} \qquad (2)$$

The coefficient k is strongly dependent on the LWA content. The degree of saturation has a negligible influence on the tensile strength. Equation 3 shows the function describing the different influences on the coefficient k:

$$\mathrm{k} = \mathrm{a} \cdot \mathrm{V}_{\mathrm{LWA}} + \upsilon \qquad (3)$$

a: slope of the curve progression, V_{LWA}: volume content of LWAs, ν: basic value, determined by the reference mixtures

Table 4 shows the coefficients and the used values for the calculation of k and the tensile strength. The slope was determined by a best fit regression analysis based on the values determined by Piehl. Based on the coefficients the tensile strength values of the mixtures, f-15, f-25 and f-30 [4], were calculated and most of them are within a 90 % confidence interval.

Table 4: Values used for equation 3

Mixture	a	v	R^2
Ref	0	0.305	-
c-d	-0.0034	0.298	0.64
c-hs	-0.0038	0.306	0.99
c-s	-0.0035	0.304	0.99
Used values	-0.00356	0.305	0.85

Figure 9 shows the results of the tensile strength model where the values were calculated based on modelled compressive strength values.

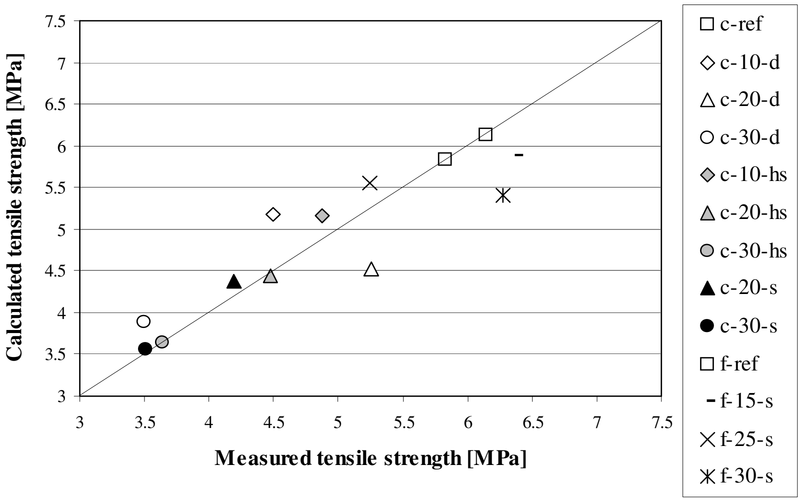

Figure 7: Results of the tensile strength calculation

The assumption of a close relation between tensile strength and LWA content is applicable. The values used for validation are positioned within a scatter band around the bisecting line. The stability index of the tensile strength model was 0.85.

7 YOUNG'S MODULUS

Figure 3 shows a significant influence of the LWA content on the elastic modulus. Videla published a simplified model for high strength concrete [16].

This approach was used since no information about the elastic modulus of a single LWA grain and its Poisson ratio was available.

$$E = a_1 + a_2 \cdot f_{comp.}^{a_3} \tag{4}$$

a_1, a_2, a_3: coefficients found by regression analysis, $f_{comp.}$: compressive strength

The coefficients were determined by best fit analysis, where a_1 was assumed to be 0 and a_3 to be 0.5. The values for a_2 ranged from 4400 for the reference mixture to 3500 for mixtures with a 30 % volume content of LWAs. Therefore the coefficient a_2 was replaced by the exponential equation (5).

$$a_2^{LWA} = a_2^{REF} \cdot e^{a_4 \cdot (-\frac{V_{LWA}}{10})} \tag{5}$$

The coefficient a_4 was determined to be 0.0865 and a_2^{REF} was 4400. Figure 9 shows the results of the model.

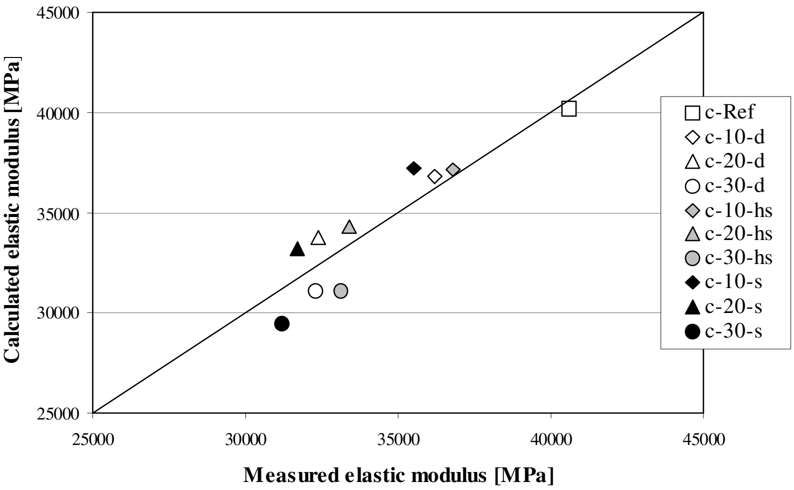

Figure 9: Results of the young's modulus calculation

The model shows good agreement with the measured values. The coefficients are dependent on the LWA attributes and their interaction with the matrix. Future research might derive these coefficients from the material attributes of a LWA.

8 CONCLUSIONS

Based on a reference mixture the compressive and tensile strength of high strength concrete with lightweight aggregate content was successfully predicted. The coefficients of the model are mainly parameters that were derived of the mixture composition, particle size distribution, and the lightweight aggregate attributes. Different types and sizes of LWA aggregates were successfully used for the validation of the model. The degree of saturation of the lightweight aggregates was also successfully considered. The models were validated with mixtures and measurements of different authors. The reliability index of the calculated results was good for all mixtures. The most important governing parameters of the model were the degree of hydration, which can be calculated based on the mixture composition, and the stored water content. Different ways to predict and estimate the maturity were presented. Future research will combine the presented strength models with the DuCOM model and should also investigate if the model can be used for lightweight sands and different types of lightweight aggregates.

REFERENCES

[1] Reinhardt H.W.; Weber, S.: Hochfester Beton ohne Nachbehandlungsbedarf, Beton- und Stahlbetonbau 92 (1997), No.2, pp. 37-41, No.3, pp. 79-83

[2] Reinhardt H.W.: Autogeneous and drying shrinkage of hybrid concrete, Concrete Science and Engineering 4(2002), pp. 77-83

[3] Bentur A., Igarashi, S. Kovler K.: Prevention of autogeneous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates, Cem. Con. Res. 31 (2001), pp. 1587-1591

[4] Lura P.: Autogeneous Deformation and Internal Curing of Concrete, PhD. thesis, Delft Technical University, 2003

[5] Beckert F.: Untersuchungen zum Schwinden und zu den Festbetoneigenschaften hochfester Betone mit Leichtzuschlag, DFG-Zwischenbericht, 2001

[6] Reinhardt H.W., Mönnig S.: Basic Concepts for a Model of Different Internal Water Sources, International RILEM-JCI Seminar ConcreteLife’06, pp. 235-244

[7] Piehl C.: Untersuchung und Modellierung des Einflusses vorgesättigter Leichtzuschläge auf hochfeste Betone, Diplomarbeit, IWB, 2006

[8] Zhang M.-H., Li L., Paramasivam P.: Shrinkage of High-Strength Lightweight Aggregate Concrete Exposed to Dry Environment, ACI Materials Journal 102 (2005), pp. 86-92

[9] Maekawa, K.; Chaube, R.; Kishi, T.: Modelling of concrete Perfomance, E&FN Spon, 1999

[10] Powers T.C., Brownyard: Studies of the physical properties of hardened Portland Cement Paste, PCA bulletin 22 (1948), Chicago

[11] Bal'sin M.J.: Abhängigkeit der mechanischen Eigenschaften pulverförmiger Metalle von der Porosität und den Grenzeigenschaften poröser metallkeramischer Materialien, Dokl. Akad. Nauk, UdSSR 67 Nr. 5, pp. 831-834, 1949

[12] Jensen O.M., Hansen P.F.: Water-entrained cement-based materials I.: Principles and theoretical background, cement and concrete research 31(2001), pp. 647-654

[13] De Larrard F., Belloc A. : The influence of Aggregate on the Compressive Strength of Normal and High-Strength Concrete, ACI Materials Journal 5 (1997), pp. 417-426

[14] Faust T.: Leichtbeton im Konstruktiven Ingenieurbau, Ernst&Sohn, 2003

[15] Bentz D., Snyder K.A.: Protected paste volume in concrete: extension to internal curing using saturated lightweight fine aggregate, Cement and Concrete Research 29(1999), pp. 1863-1867

[16] Videla C., Gaedicke C.: Modelling Portland Blast Furnace Slag Cement HPC, ACI Materials Journal, 101(2004), No. 5, pp. 365-375