EFFECT OF AGGREGATE PARTICLE SIZE ON MECHANICAL PROPERTIES OF CONCRETE

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ABSTRACT

Based on fracture mechanics considerations two models are presented which can explain several aspects of some mechanical properties of concrete. The first model law describes the dependence of notch sensitivity of brittle materials on specimen size, fracture toughness and tensile strength. The predictions of the model law are substantiated by experiments. In the second part of this paper a theoretical and experimental analysis of crack formation in concretes and model concretes is presented. These investigations lead to the model of grain size dependent crack formation in concrete. The model indicates that cracks due to internal desiccation exist in concrete and are formed at aggregates only with a diameter larger than a given critical value. Using this model it is possible to understand some aspects of thermal expansion and shrinkage of concrete as well as the dependence of tensile strength on aggregate size.

KEYWORDS

Notch sensitivity; specimen size; aggregate grain diameter; grain size dependent crack formation, flexure strength.

INTRODUCTION

One potential approach for a better understanding of the fracture mechanisms of hardened cement paste, mortar and concrete is given in the form of linear elastic fracture mechanics (LEFM). The applicability of LEFM to these materials seems obvious, since hardened cement paste, mortar and concrete show distinctly elastic and brittle behavior when loaded in tension. A great number of experiments have shown that LEFM is indeed applicable to hardened cement paste, but not to mortar or concrete. This result is not surprising, as homogeneity of the material is one of the necessary conditions for the applicability of LEFM .

Though LEFM is not applied to the design of concrete structures, it provides a valuable tool for explaining several - hitherto only incompletely understood aspects of concrete fracture. In this paper two models are developed, which are based on LEFM and which give a better insight into mechanisms of concrete cracking. In the first part of this paper an equation is presented, which describes the relation between notch sensitivity of a brittle material such as hardened cement paste and material properties as well as specimen dimensions. In the second part the model of grain size dependent crack formation is introduced. According to this model cracks in concrete which are due to shrinkage as a consequence of internal desiccation are initiated only at aggregate grains above a critical size. The validity of both models is tested by appropriate experiments.

NOTCH SENSITIVITY OF HARDENED CEMENT PASTE, MORTAR AND CONCRETE

Theoretical Study

In a recent paper the authors (1980) deduced a model law for the notch sensitivity of brittle materials under the only condition of applicability of LEFM. For the case of four-point-flexure the following equation for the notch sensitivity had been derived:

$$\sigma_n/\beta_t = K_{IC}/\{\beta_t \cdot \sqrt{a}\,(1 - a/b)^2 \cdot F(a/b)\} \qquad (1)$$

with K_{IC} - fracture toughness
a - crack length
b - specimen depth
$F(a/b)$ - correction function for four-point bending.

This expression gives a unique relationship between notch sensitivity and relative crack length for a specimen to which LEFM applies. In Fig. 1 a numerical evaluation of eq. 1 is presented using material parameters, which are the result of own experiments on hardened cement paste. Dashed rather than solid lines have been used where the conditions for minimum specimen dimensions normally applied in fracture mechanics are violated.

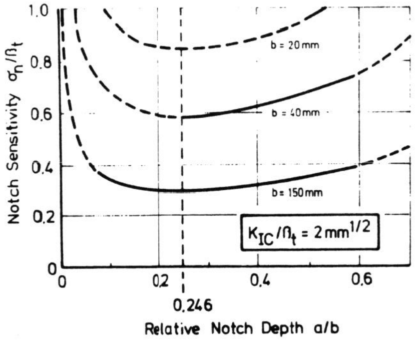

Fig.1. Dependence of notch sensitivity on crack length (eq.1)

Figure 1 shows, that the frequently observed occurence of a minimum of relative net failure stress can be explained theoretically in a quite simple manner. Furthermore Fig.1 demonstrates that notch sensitivity is a necessary but not a sufficient condition for the applicability of LEFM to notched specimens.

Experimental Study

The objective of this study has been to investigate the applicability of the model law to hardened cement paste, mortar and concrete specimens. Notched and unnotched specimens were tested in four-point-flexure. As the model law predicts a maximum notch sensitivity at a relative notch depth of 0,246, a relative crack length of 0,25 has been chosen. According to eq. 1 the specimen size has an important influence on notch sensitivity. Therefore, specimens with three different cross-sections 20 by 20 mm, 40 by 40 mm and 100 by 150 mm have been investigated. Furthermore, neat cement paste, model mortar (MM) with aggregate sizes of 1 to 2 mm and 2 to 4 mm, respectively, as well as model concretes (MC) with aggregates ranging from 4 to 8 mm and 16 to 32 mm, respectively, have been studied. A water/cement ratio of 0,40 has been kept constant throughout.

The notches at mid span of the specimens have been manufactured by inserting two brass foils with a thickness of 25 μm each. After casting the specimens have been covered with wet burlap for one day. Then they were demolded and stored up to an age of loading of seven days in a saturated lime solution at a temperature of (2o ± 1) °C.

In Table 1 the tensile strength β_t of the unnotched specimens, the net failure stress σ_n of the notched specimens as well as the notch sensitivity values σ_n/β_t have been summarized.

TABLE 1 Results of Test Program

Material		Specimen Size		
		20x20x80 mm	40x40x160 mm	100x150x700 mm
Paste	β_t σ_n σ_n/β_t	7,24 4,35 0,60	7,29 4,16 0,57	6,64 2,79 0,42
MM 1/2	β_t σ_n σ_n/β_t	7,o5 5,93 0,84	6,82 4,96 0,73	6,98 4,29 0,61
MM 2/4	β_t σ_n σ_n/β_t	6,68 5,75 0,86	6,37 4,90 0,77	
MC 4/8	β_t σ_n σ_n/β_t		5,67 4,49 0,79	6,20 4,15 0,67
MC 16/32	β_t σ_n σ_n/β_t			3,73 3,22 0,86

A quantitative comparison of measured and predicted (eq. 1) values is questionable because:

a) It is known that slow stable crack growth prior to fracture occurs in hardened cement paste specimens. As a consequence the apparent K_{IC}-values are dependent on specimen size as observed by Higgins and Bailey (1976).
b) As a consequence of their inhomogeneity, in mortar and concrete multiple crack growth occurs, requiring a specimen size considerably larger than those used in this study.

Nevertheless, it is evident that the trends observed in the experiments are correctly predicted by the model law:

- As illustrated in Fig. 2, the notch sensitivity of all materials decreases with increasing specimen size.
- As shown in Fig. 3, the notch sensitivity decreases with increasing aggregate size.

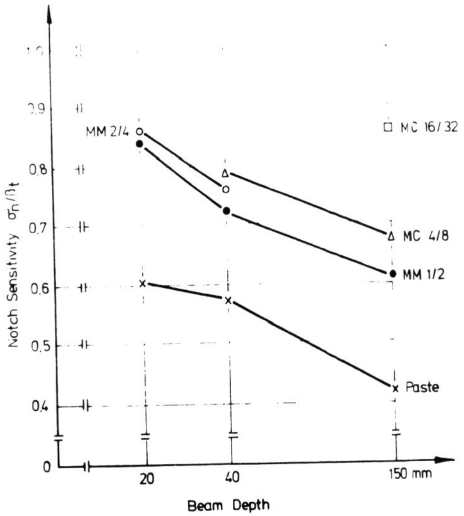

Fig. 2. Influence of specimen size on notch sensitivity.

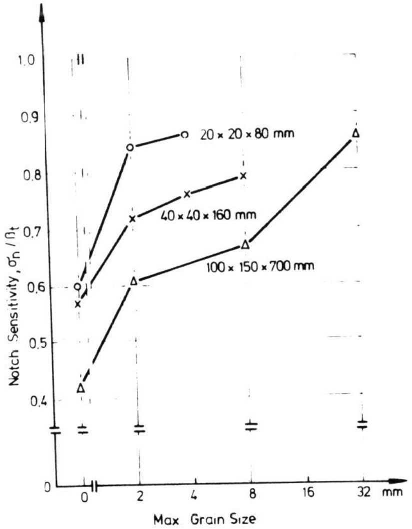

Fig. 3. Influence of maximum aggregate size on notch sensitivity.

The decrease of notch sensitivity with increasing aggregate size is consistent with the predictions of the model law, as it is generally agreed upon that K_{IC} (apparent, effective or pseudo-fracture toughness) of mortar or concrete increase with increasing aggregate size, whereas the tensile strength decreases, as documented in Table 1. Thus K_{IC}/β_t is increased, leading to a reduced notch sensitivity.

CRACK FORMATION IN CONCRETE

Apart from the dependence of notch sensitivity on material properties and geometrical parameters the results given in Table 1 offer another interesting aspect: For all specimen geometries it is evident that the tensile strength of the unnotched specimens has its highest value in the case of the hardened cement paste, and decreases with increasing aggregate size. A similar dependence of tensile strength on aggregate diameter has been observed by others (Kellermann, 1932; Jones and Kaplan, 1957), though, to our knowledge, a convincing explanation for this behavior has not yet been proposed. A possible explanation is given by the fact that in mortars or concretes with constant aggregate concentration the effective w/c-ratio decreases with decreasing aggregate diameter, because of the increase in specific surface of the aggregates. If this were the main reason for the observed behavior, there should be a pronounced decrease of tensile strength of mortar compared to the strength of neat cement paste. In these tests, this decrease - when observed - is small and the most significant strength reduction occurs for the concrete with the large aggregate sizes.

There are however, two other possible mechanisms which can explain the distinct decrease of tensile strength of concretes made of large aggregates. Both mechanisms take into account crack formation:

a) Bond cracks or imperfections of the aggregate-cement paste interface may exist in the mortars and the concretes prior to loading. They may be caused by bleeding or by early shrinkage. Naturally the bond cracks would be the larger the larger the aggregates causing the observed decrease of tensile strength with increasing aggregate size.
b) Another possible explanation is based on the model of grain size dependent crack formation. This model allows the conclusion that shrinkage cracks in hardened cement paste are initially generated at large aggregate particles but not at particles whose size is less than a limiting value. In the following sections it is attempted to confirm this model by theoretical considerations and by appropiate experiments.

Autogeneous Cement Paste Shrinkage and Crack Formation in Concrete

It is generally known that cement paste reduces its volume in the course of hydration even if external drying is prevented. The causes for the volume reduction are chemical and physical. The chemical effect is due to the observation that the hydration products occupy a volume smaller than the volume of the initial products. The physical influence is mainly connected with self desiccation leading to changes of capillary forces, specific surface energy and disjoining pressure in the hardened cement paste (Wittmann, 1974; Setzer, 1975).

At our institute we are investigating the early shrinkage behavior of cement pastes using a special dilatometer. A detailed description of the experimental set up is given elsewhere (Ziegeldorf and Hilsdorf, 1980). In Fig.4 the shrinkage behavior of a cement paste with a water/cement ratio of 0,4 is shown. During the experiment the cement paste was sealed in a water-tight polyethylene envelope. The temperature was $(20 \pm 1)^{o}$C.

Considering the half-logarithmic presentation, Fig.4 can be interpreted as follows: The rate of shrinkage in the time interval from mixing till final set (about 6 h after mixing) is constant (dormant period). After reaching a maximum value of shrinkage, a period of expansion is observed, which lasts from the 10th to the 24th hour. Then a new shrinkage period begins (physical shrinkage) at a reduced rate.

As the authors of this paper assumed the existence of cracks in unloaded concrete specimens due to cement paste shrinkage, an experimental investigation of the early tensile properties of hardened cement paste was undertaken parallel to the shrinkage experiments. In these tests the σ-ε-diagrams of cement prisms were measured in 4-point-flexure.

To ascertain comparability of shrinkage and tension experiments the flexure specimens haved been sealed. In the tests the specimens exhibited nearly ideal linear-elastic behavior, independend of specimen age (first measurement: 7 h after mixing).

In Fig. 5 the ultimate tensile strains of the 4-point-flexure beams as obtained in the above mentioned experiments are compared with the shrinkage behavior of the paste. There, the volumetric strain as obtained from the dilatometer measurements has been transformed into length changes. The origin of the shrinkage strains is taken at an age of 8 h corresponding to the final set of the cement paste.

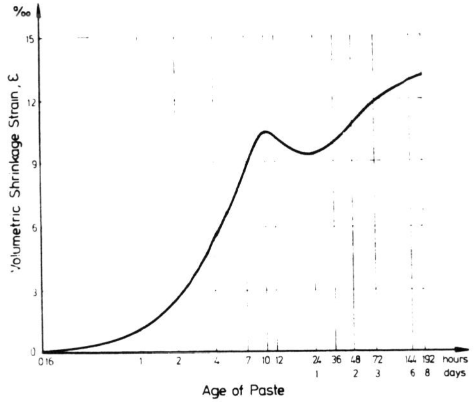

Fig.4. Shrinkage behavior of cement paste

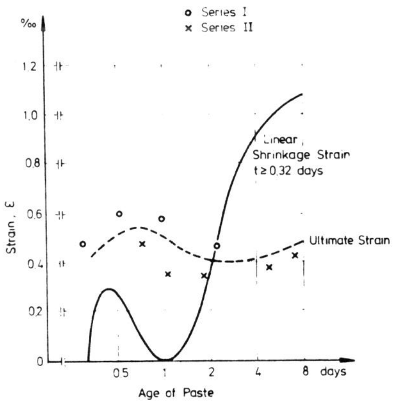

Fig.5. Comparison of shrinkage strain and ultimate strain

Fig. 5 shows that after eight days the shrinkage of sealed neat cement paste is more than twice the failure strain of sealed neat cement paste specimens loaded in flexure. Neglecting relaxation effects these experiments allow the conclusion that in concrete the formation of cracks due to restraint of shrinkage of cement paste by the aggregates is probable even if drying is prevented.

Particle Size Dependent Crack Formation

Using the theory of elasticity it can be shown that the maximum stresses at single particles in an infinite isotropic matrix - e.g. caused by differential thermal expansion or differences in the shrinkage behavior of the two components - is independent of particle diameter (Weyl, 1959; Selsing, 1961). However, Binns (1962) and Davidge and Green (1968) showed, that during the cooling of various particulate ceramic composites, cracks only formed adjacent to the larger particles and not to the smaller ones. Davidge and Green recognized this inconsistency and pointed out that since the stresses are highly localized, only a limited amount of stored strain energy is available for crack extension. They showed that the residual stored strain energy depends on the third power of the size of the particle, whereas the energy necessary to form the crack can be related to the square of the size of the particle. Assuming the formation of hemispherical cracks around the particles and using an energy balance approach corresponding to the procedure as chosen by Griffith (192o) they concluded that cracks will form only adjacent to particles greater than a critical size. Some years later Lange (1974) extended the theory of Davidge and Green. He pointed out, that crack propagation at second phase particles embedded within a matrix phase will occur when $\sigma^2 R > C$ (C = constant).

GRAIN SIZE DEPENDENT CRACK FORMATION IN CONCRETE

Theoretical Considerations

The considerations cited above concerning the crack extension in two-phase ceramics cannot be applied to concrete without further ado, since an analysis of stresses and strains in concrete is complicated - among others - by stress relaxation and high volume concentration of aggregates. On the other hand there are some aspects which encourage the application of the model to concrete:

- As mentioned above, hardened cement paste exhibits nearly ideal linear-elastic behavior, even at an early age, thus fulfilling one of the conditions for the applicability of LEFM.
- Neglecting relaxation effects the stresses at aggregates as produced by early shrinkage of the cement paste matrix largely exceed the value necessary for crack extension.

The possibility of grain size dependent crack formation in concrete can be analysed using an energy balance approach analogous to the procedure as reported by Davidge and Green. The basis of our analysis is a simplified concrete model which consists of a hardened cement paste plate in which the aggregates with a volume concentration of 5o% are embedded as cylinders of a given diameter (see Fig.6). The stresses in such a concrete model have been calculated by Fein (1971) and Hsu (1962) for different ratios of modulus of elasticity of cement paste and aggregate, resp.

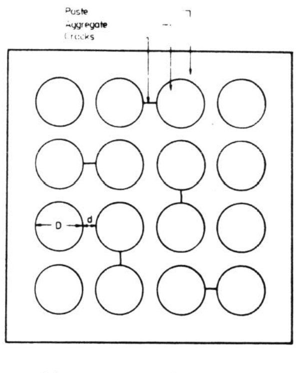

Fig. 6. Two-dimensional model of concrete.

The elastic energy U in an element of material subjected to orthogonal tensile or compressive stresses σ_1, σ_2 and σ_3 is:

$$U = 1/2E \cdot \{(1+\nu) \cdot (\sigma_1^2 + \sigma_2^2 + \sigma_3^2) - \nu(\sigma_1 + \sigma_2 + \sigma_3)^2\} \qquad (2)$$

Based on the analysis of Fein the elastic strain energy has been evaluated which is stored in an element with the side length of (D+d). An aggregate cylinder with a diameter D is located at the center of the element (see Fig. 6). For the model concrete with a volume concentration of the aggregates of 50 %, d/D = 0,253. The following result has been obtained:

$$U_{total} = U_{matrix} + U_{aggregate} = (0{,}267/E_m + 0{,}108/E_a)\sigma_s^2 \cdot D^2 \qquad (3)$$

with: $\sigma_s = E_m \cdot \varepsilon_s$
E_m = modulus of elasticity of matrix
E_a = modulus of elasticity of aggregate
ε_s = shrinkage strain of paste
D = diameter of aggregate

As shown by experiments (see next section) in such a simplified model concrete cracks develop at the most narrow section of the hardened cement paste between two aggregate cylinders. Only cracks bridging the entire distance between two aggregate cylinders have been observed. The energy necessary for the development of one crack (height: 1 mm; width: d mm) is:

$$U_{surface} = 2 \cdot \gamma \cdot d = 0{,}506 \cdot \gamma \cdot D \qquad (4)$$

When a crack is to be formed, this surface energy must be supplied by the elastic energy which is stored in two adjacent elements. However, only part of the energy as given by eq.3 is available for crack extension. Based on rough estimates this fraction is assumed to be 1/10 of the total strain energy. Now eq. 3 and 4 can be combined resulting in the following equation:

$$D \geq \frac{5{,}06 \cdot \gamma}{2 \cdot (0{,}267/E_m + 0{,}108/E_a)\sigma_s^2} = C/\sigma_s^2 \qquad C = \text{const.} \qquad (5)$$

With a surface energy of the hardened cement paste of $6 \cdot 10^{-3}$ Nmm/mm^2 (medium value of literature values) and E_m = 10.000 N/mm^2, E_a = 210.000 N/mm^2, ε_s = 0,05% we obtain

$$D \geq 22{,}3 \text{ mm} \qquad (6)$$

Thus, in a model concrete as described above with a paste shrinkage of 0,05% cracks would occur if the aggregate diameter exceeds 22,3 mm and if stress relaxation does not take place. Naturally it is not to be expected, that the latter assumption is fulfilled in practice, especially in young pastes.

Experimental Investigations

Following the theoretical considerations concrete models have been investigated in which steel cylinders of various diameters with a volume concentration of 50% have been embedded in a cement paste matrix (see Fig.6). In the experiments specimens with 16 cylinders and three different cylinder diameters have been used: 4 mm, 1o mm and 25 mm. After casting the specimens were sealed and stored in a room with a temperature of (2o ± 1)°C. After 24 hours the specimens were demolded and sealed using a thin polyethylene sheet. As the polyethylene is transparent, crack formation in the sealed specimens can be investigated in a microscope.

It had not yet been possible to optimize the experimental set up of the present experiments. E.g. a slight moisture loss and thus drying shrinkage could not be avoided. Nevertheless, the first results of the tests confirm the model of grain size dependent crack formation. After 7 days of aging, 5 cracks - bridging the aggregate grains at the narrowest part of the cement paste - had been detected in the model concrete with 25 mm-aggregates. No cracks had been detected in the model concrete with 1o mm-aggregates and one crack was observed in the model concrete with 5 mm-aggregates. The experiments are being continued.

Other Concrete Properties

Apart from these experiments, there are other test results which confirm the model of grain size dependent crack formation:

- In this paper experiments had been presented, in which a distinct decrease of tensile strength of model concretes had been observed for large aggregate diameters. According to the model it can be assumed that cracks have formed in the model concrete with large aggregate diameter thus reducing the tensile strength, but not in the model concrete with small aggregates.
- In another test series the authors (1979) observed some anomalies in the thermal expansion of different concretes. The most significant result obtained had been, that for equal volume fractions the thermal properties of coarse aggregates have a more pronounced effect upon thermal expansion of concrete than those of fine aggregates. It was shown that this behavior can be explained by assuming crack formation at larger aggregates but not at small ones.
- It has been observed repeatedly that - all other parameters being equal - drying shrinkage of concrete decreases with increasing aggregate size (Carlson, 1938; Alexander and Wardlaw 1959;Cook, 1978). A similar trend has been observed for the early shrinkage of mortars and concretes under sealed conditions. Such behavior can be explained by the generation of cracks which tend to reduce the volume reduction. According to our model the cracks form only if a limiting aggregate size is exceeded.

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