Effects of various factors on concrete strength and crack-resistance

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Abstract. This paper reviews the methods for evaluation of strength and crack-resistance from the perspective of fracture mechanics and slow expansion of the most dangerous main cracks. Complete concrete stress-deformation and destruction diagrams with the fracture work and energy evaluation have been obtained through testing as well as the force parameter such as the critical stress intensity ratio has been determined. The analysis of test results has proved that crack-resistance of concrete can change depending on the type, size and volumetric content of the aggregate and also on the water-cement ratio, age, hardening conditions and heating temperature of concrete.

1. Introduction

The up-to-date construction industry is inextricably bound up with the use of various construction materials, especially concretes having high strength, crack-resistance and longevity properties. When in service the concrete structures are exposed to various loads and effects including the exposure to environment conditions. Since the concrete structure is not homogeneous, there exists a risk of formation and expansion of micro-cracks which may be transformed into one or several main macro-fractures. The scientific research of concrete destruction due to various effects with evaluation of physical and mechanical properties of materials will enable evaluation of the critical ultimate operating loads for the structures.

2. Importance

The energy- and force-based approaches are practised to study the brittle fracture processes [1-4] with a view to evaluate the strength and crack-resistance properties. According to those approaches, the description of deterioration processes of concretes (which are considered to be a quasi-brittle composite material) is connected with the presence and further expansion of micro- and macro-inhomogeneities in their structure. There also exists a well-known approach connected with the fluctuating heat motion of particles within the crystalline lattice of materials [5, 6]. Local overstressing of atomic links is caused by external load which may lead to kinetic expansion of fracture processes, especially in the defective areas of non-homogeneous structure of materials.

The multi-component structure and considerable inhomogeneity of heavy concretes do not make it possible to reliably evaluate their crack-resistance and longevity with account of various effects including process factors.

For that reason, the critical task at present is the accumulation of testing data for optimized approach to integrated evaluation of concrete strength and crack-resistance.
3. Problem statement
Development of optimal heavy concrete mixes having pre-determined physical and mechanical properties is connected with evaluation of the strength and crack-resistance properties of concrete components. The most critical issue in such case is the identification of the said parameters with account of aggregate type, maximum size of its grains and its quantity. It is necessary to evaluate the effect of water-cement ratio, degree of hydration of the cementing agent on the crack formation process depending on the strengthening terms and conditions. When heavy concretes are exposed to increased temperatures, additional intra-stresses arise within their structure that leads to crack expansion and a lower strength.

The fracture mechanics methods [7-15] and the developed direct speed measurement methods of the main crack expansion are most widely used for evaluation of various effects and for identification of regular patterns of concrete cracks formation and expansion. The use of those methods enables the development of various new concrete mixes which will have expectedly improved physical and mechanical properties.

Crack resistance was evaluated by fracture mechanics methods through evaluation of energy and force parameters in the course of total destruction test of concrete.

In order to obtain the strength and crack resistance values the concrete samples were tested till their total destruction to build a complete stress deformation diagram. During the scientific research the optimal sample sizes and the three-point bending load scheme were selected. During preparation for the test, the sample prisms were notched up to a pre-set depth in their most dangerous bottom sections, from which a controllable expansion of the main crack was expected as the mechanical load grew higher unless the total destruction occurred.

Based on numerous three-point bending stress tests [16-21] for obtaining the complete deformation stress and fracture diagrams, the optimal sizes of sample-prisms are 100х100х400 mm, and the notching depth (initial main crack) comprised half of the sample's section height: a = 0.5h, where h is the height of the sample. By using of strength members in addition to the standard hydraulic press [15] the selected sample sizes and the size of the initiating crack enabled obtaining of complete stress deformation diagrams for all heavy concrete mixes and therefore, the energy and force parameters of the fracture toughness.

The experimental research was aimed at obtaining of complete “F Load – f deformation” curves with subsequent evaluation of fracture energy - $G_{1c}$ for the area covered by the diagram which relates to the sample’s fracture area that showed the main crack expansion [2, 7, 8, 11-13].

The force criterion of the fracture toughness, and namely, the critical stress intensity coefficient $K_{IC}$, was evaluated with account of the concrete modulus of elasticity – E as per the known dependence [2]. As a result the hardening process is accelerated and the homogeneous compact and strong structure of concrete is formed.

4. Theoretical part
The coarse aggregate, water-cement ratio, age of concrete and other characteristics have a considerable effect on the crack-resistance of concrete. In order to evaluate crack expansion parameters, the experimental research of concretes with the following features was conducted: type of aggregate, its maximum size and volumetric content, water-cement ratio and degree of hydration which was adopted based on the preliminary tests, and the age of concrete. The prizm-shaped samples sized 100х100х400 mm and having a notch depth of 0.5h were tested as with such sample size and length of crack the stable crack toughness values were observed. Simultaneously, the mathematical plan of the limited 4-factor experiment was developed to evaluate the dependence of crack resistance of concrete on the cumulative effect of the properties of its components. The following variable factors were selected: water-cement ratio - W/C, age of concrete linked to the degree of hydration of the cementing agent - $\alpha$, maximum size of coarse aggregate - $D_{max}$, volumetric content of the coarse aggregate - $V_{agg}$. The following parameters were selected for optimization: crack resistance values $K_{IC}$ and $G_{1c}$, compression strength value $R_b$ and bending tensile strength $R_{btf}$. Based on the experimental conditions and in
accordance with the planning matrix, the developed heavy concrete mixes were prepared. For the previously conducted [16] research the average concrete humidity value was used as an additional variable factor. The obtained equations revealed but a minor effect of this parameter on the crack resistance of concrete.

5. Results of experimental studies
The experimental research was aimed at building of complete concrete stress-deformation diagrams for different concrete aggregates as well as at evaluation of strength and crack-resistance of the test samples.

Analysis of the test results proved that the fracture energy and the stress intensity coefficient are increased as the aggregate grows in strength (figure 1 and table 1).

The quartzite and granite aggregates which have the highest strength properties contributed to high crack-resistance parameters. The quartzite- or keramzit-based concretes showed crack expansion in the contact zone in contrast to the concretes made with limestone and keramzit aggregates (having a lower strength) where the fracture process mainly affected the aggregate. And much more destructive energy [7, 12] was needed for the crack to bend round the aggregate grains.

The concrete made of quartzite proved to have 2.2 times higher stress intensity coefficient vs. concrete composed of porous keramzit aggregate. As the aggregate (granite) grows in size from 5 to 20 mm, $K_{1c}$ is increased by 23 % with a corresponding 14 % increase in strength $R_{btf}$ (table 1). Granite was selected to be a concrete aggregate since it is widely used for load bearing items of PC structures and for the cast-in-situ concrete, too.

If the volume of the coarse aggregate is increased from 40 % to 70 %, the strength of concrete $R_{btf}$ is increased by 43 % with the corresponding 35 % increase of the stress intensity coefficient and 58 % increase of fracture energy $G_{1c}$ (table 1). The obtained data are aligned with the similar test results presented by other researchers [7, 12, 14].

Water-cement ratio, age of concrete (due to increase of degree of hydration of the cementing agent) and a higher temperature have a considerable effect on concrete strength and crack resistance.

If the water-cement ratio is decreased from 0.6 to 0.38, the fracture energy $G_{1c}$ and the critical stress intensity coefficient $K_{1c}$ are increased by 66 % and the strength of samples $R_{btf}$ will be by 48 % higher, too (table 2). Such differences are a regular pattern due to increased density and changed porosity of concrete.
Table 1. Effect of coarse aggregate on concrete strength and crack resistance.

| Name      | $R_b$, MN/m$^2$ | $R_{bfr}$, MN/m$^2$ | $E$, MN/m$^2$ | $G_{1c}$, N/m | $K_{IC}$, MN/m$^{3/2}$ | $F_c$, N |
|-----------|-----------------|---------------------|---------------|---------------|------------------------|---------|
| Type of aggregate | | | | | | |
| Quartzite | 33.9            | 3.48               | 32,200        | 65.2          | 1.45                   | 1,611   |
| Granite   | 32.1            | 3.39               | 27,400        | 59.2          | 1.28                   | 1,564   |
| Limestone | 28.7            | 2.93               | 23,700        | 49.8          | 1.09                   | 1,356   |
| Keramzit | 15.5            | 1.8                | 12,800        | 32.6          | 0.65                   | 833     |
| Maximum size of (granite) aggregate, mm | | | | | | |
| 5         | 29.2            | 2.97               | 24,600        | 43.8          | 1.04                   | 1,375   |
| 10        | 29.8            | 3.12               | 25,800        | 46.5          | 1.1                    | 1,444   |
| 15        | 30.6            | 3.24               | 26,500        | 55.0          | 1.21                   | 1,500   |
| 20        | 32.1            | 3.39               | 27,400        | 59.2          | 1.28                   | 1,564   |
| Volumetric content of aggregate, % | | | | | | |
| 70        | 42.3            | 3.6                | 28,500        | 61.1          | 1.32                   | 1,667   |
| 60        | 31.5            | 3.3                | 28,100        | 57.4          | 1.27                   | 1,528   |
| 50        | 26.4            | 2.87               | 26,200        | 45.2          | 1.09                   | 1,329   |
| 40        | 23.8            | 2.51               | 24,900        | 38.7          | 0.98                   | 1,162   |

The degree of hydration of the cementing agent has a considerable effect on the change in porosity which is decreased from 18 % when the concrete age is 14 days to 12.2 % after three months of hardening. As the structure of concrete is modified, its properties (particularly, strength and crack resistance) are changed, too. The tests of concrete aged 7, 14, 28 and 65 days which were conducted to build complete stress-deformation diagrams (table 2) showed the trend of continuous crack resistance increase over time. Within the 2 months’ hardening period of concrete the stress intensity coefficient increased by 33 % and its strength $R_{bfr}$ - by 25 %. The crack resistance parameter was changing during the first 28 days, after 65 days the growth of $G_{1c}$ and $K_{IC}$ nearly stops, especially in case of cured concrete.

Table 2. Effect of various factors on concrete strength and crack resistance.

| Factor | $R_b$, MN/m$^2$ | $R_{bfr}$, MN/m$^2$ | $E$, MN/m$^2$ | $G_{1c}$, N/m | $K_{IC}$, MN/m$^{3/2}$ | $F_c$, N |
|--------|-----------------|---------------------|---------------|---------------|------------------------|---------|
| Water-cement ratio | 43.8            | 4.6                 | 29,800        | 120.3         | 1.89                   | 2,130   |
| 0.45   | 36.7            | 3.9                 | 28,300        | 89.6          | 1.6                    | 1,806   |
| 0.5    | 32.1            | 3.39                | 27,400        | 59.2          | 1.28                   | 1,564   |
| 0.6    | 31.4            | 3.1                 | 26,900        | 48.5          | 1.14                   | 1,435   |
| Concrete age, days | 24.9            | 2.7                 | 25,800        | 35.6          | 0.96                   | 1,250   |
| 14     | 30.8            | 2.98                | 26,300        | 44.9          | 1.09                   | 1,380   |
| 28     | 31.7            | 3.22                | 27,150        | 53.5          | 1.21                   | 1,491   |
| 65     | 32.1            | 3.39                | 27,400        | 59.2          | 1.28                   | 1,564   |
| Heating temperature, °C | 32.1            | 3.39                | 27,400        | 59.2          | 1.28                   | 1,564   |
| 20     | 32.1            | 3.39                | 27,400        | 59.2          | 1.28                   | 1,564   |
| 110    | 22.3            | 2.43                | 23,100        | 57.4          | 1.25                   | 1,125   |
| 300    | 20.2            | 2.3                 | 22,970        | 57.7          | 1.15                   | 1,065   |
| 600    | 13.9            | 1.65                | 12,350        | 46.4          | 0.76                   | 764     |
In the course of processing of the mathematical planning matrix the regression equations were obtained which linked the strength $R_{btf}$ and crack resistance $G_{1c}$, $K_{1c}$ parameters of concrete and the cumulative changes in properties of its components.

$$K_{1c} = 1.067 + \frac{0.039}{(W/C)^2} + \frac{0.417}{D_{\text{max}}^2} + \frac{0.0092}{V_{\text{agg}}^2},$$

Average approximation error $S = 4\%$.

$$G_{1c} = 50.85 + \frac{3.132}{(W/C)^2} + \frac{9467}{\alpha^2} + \frac{18.333}{D_{\text{max}}^2} + \frac{0.3691}{V_{\text{agg}}^2},$$

Average approximation error $S = 7\%$.

$$R_{btf} = 3.086 + \frac{0.074}{(W/C)^2} + \frac{237}{\alpha^2} + \frac{6.833}{D_{\text{max}}^2} + \frac{0.0107}{V_{\text{agg}}^2},$$

Average approximation error $S = 2\%$.

The value of the objective function coefficient in the regression equations allows to evaluate the effect of each variable factor on the strength and crack resistance parameters. According to the obtained dependences (1-3) the analysis of experimental data has expectedly proved that the strength and crack resistance of concrete increase as the W/C is decreased, the size $D_{\text{max}}$ and aggregate volume $V_{\text{agg}}$ are increased as well as the concrete age which is linked to the degree of hydration of the cementing agent $\alpha$.

6. Conclusions
It was proved that the crack-resistance property of concrete changes depending on the type, size and volumetric content of the aggregate and also on the water-cement ratio, age, hardening conditions and heating temperature. In the course of the experimental data processing based on the preliminarily developed mathematical planning matrix the regression equations were obtained which linked the strength $R_{btf}$ and crack resistance $G_{1c}$, $K_{1c}$ parameters of concrete to changes in properties of its components.

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