Creep of fine-grained carbonate concrete with a complex additive

V V Belov1*, P V Kuliae2 and T R Barkaya2

1Department of Construction materials and technologies, Tver State Technical University, 22 Afanasiya Nikitina Quay, Tver, 170007, Russia
2Department of Constructions and Facilities, Tver State Technical University, 22 Afanasiya Nikitina Quay, Tver, 170007, Russia

* vladim-bel@yandex.ru

Abstract. Fine-grained carbonate concretes (FGCC) have presently proved to be quite applicable with good parameters on crack- and freeze-thaw performance as criteria of durability and reliability of building materials and structures. The purpose to enhance deformative characteristics of FGCC is actually a search for economically and ecologically proven ways for it. The paper presents the results of strain’s study of fine-grained carbonate concretes with limestone fines and superplastisizer. Strains are classified as instant, short-term and long-term (creep). A method of planning experiment is used in the study. To measure strains, electric gauges and clock-type indicators were used. It was shown that a complex additive enhances both durability and performance of fine-grained carbonate concretes due to modification of their structure formation and hardening.

1. Introduction

One of the urgent tasks of the construction industry is to obtain building composites with improved physical, mechanical and operational characteristics. This is due to the need to develop new compositions of FGCC at different levels of exposure [1, 2]. In the FGCC, there is a so-called matrix consisting of cement paste and various additives and a rigid skeleton of aggregate. Reducing the level of deformations of the FGCC is curtailed to the usage of forth-described processes [3]: smoothing of hydration chain via noticeably flattened spread of cement granules in the volume of the FGCC; physical displacement of water from air and capillary micropores, and its partial transfer to the gel region.

The correct dosage, the degree of dispersion and the technology of introducing additives lead to a reduction in the deformations of FGCC, making them more durable and resistant to aggressive media [4].

The works [5, 6, 7] present modern studies of FGCC with mineral additives and the influence of various factors on its physical and mechanical properties. Creep deformations are no less important operational characteristics of FGCC [8]. They are influenced by such terms as water-hard-staff ratio, the aggregate bulkness, the tiny structure of the binder, the dampness, the concrete age at the time of loading, and the load value [9, 10, 11].

The effect of parameters like structure, consistence of concrete, the dosage of plasticizing agents and inert additions is mentioned in the works, wherein the effect of the limestone finest filler upon the
rheology and technological properties of concrete is also discussed [12, 13, 14]. The method of assessing the durability of concretes on a composite binder is considered in [15].

Thus, the analysis of the published works, both the above and others on this topic, shows that when developing the FGCC technology, special attention is paid to improving the strength, frost resistance, resistance to cyclic loads and abrasion (for example, when obtaining road structures), which is not always possible to implement with the existing methods of designing FGCC compositions and production technologies. This is especially true for the task of increasing the crack resistance of these concretes. Therefore, it is necessary to improve scientific methods and methods for improving the operational and technological properties of FGCC, first of all, their crack resistance and durability.

The solution of this problem requires the involvement of modern ideas on the regulation of the grain composition of limestone coarse fraction, with the regulating of the FGCC compositions through the use of a fine filler from the limestone crushing and screening, and plasticizing additives, the joint use of which can create a synergistic effect. The above circumstances determine the objectives of this work.

2. Models and methods

When analyzing the deformative properties of a material, the following types of creep deformations are distinguished: conditionally instantaneous, short-term and long-term. In this paper, we consider short-term creep, the duration of which \( t_0 \) is small compared to the age of concrete \( \tau_0 \), in which the load is applied, making 100 days.

In this case, the modulus of concrete can be taken as a constant value

\[
E(\tau) = E(\tau_0) = E = \text{const}
\]

For constant stresses \( \sigma \), the deformations function can be taken in the form

\[
\varepsilon(t) = \frac{\sigma}{E} + \varepsilon_{cr}
\]

The first term is a strain that develops at the moment of application of the load, independent of time [7].

The second term is the creep strain:

\[
\varepsilon_{cr} = C\tau_0 \times \sigma \times \left[1 - e^{-\gamma(t-t_0)}\right]
\]

The determination of creep deformations was carried out on samples - cubes of 100x100x100 mm. This is quite consistent with previous studies on the determination of the deformative properties of fine-grained concretes operating under complex loading conditions [11]. Loading of the samples was carried out step by step. The load per step was assumed to be 50 kN. Instantaneous strain measurements were performed using the Winston strain gauge bridge. A high-precision electronic galvanometer with a resolution of \( 10^{-7} \) was used. The base of the strain gages was 20 mm. To compensate for the contact (local) stresses when transferring the load to the sample, the scheme of a free (hinged) upper support and a fixed lower one was used. The task was to evaluate the development of instantaneous and long-term deformations for fine-grained concrete in two orthogonal planes. Therefore, two strain gauges were used (in the vertical and horizontal axes on each face).

The actual value of the compressive load on the sample, in kN, was established by the dynamometer.

The following method was used to study creep deformations. The frames were used for the tests, but the measuring instruments were clock-type indicators and a dynamometer (Figure 1).
Figure 1. Creep short-term and instant (a) and short- and long-term (b) strain test devices with electric gauges, a metric ruler, levelling planer with scales, dynamometers, and clock-type indicators.

The deformative properties of FGCC are controlled at three levels: micro-level, meso- and macrolevel. These levels reflect the features of the interactions of structure-forming elements in fine-grained carbonate concrete, which affect, among other things, the deformative behavior of the FGCC.

One way to reduce creep deformations is to create a uniform and compact concrete structure. This is facilitated by the creation of a contact structure of a compacted type, with a minimum amount of voidness, as well as the introduction of a limestone micro-filler into the concrete structure.

To create a contact structure of the compacted type of carbonate concrete, the limestone aggregate in the work was optimized according to the Funk-Dinger formula in accordance with Table 1.

| № | Sieves (mm) | Partial (g) | Partial (%) | total residues (%) | Pass (%) |
|---|-------------|-------------|-------------|-------------------|---------|
| 1 | 0.16        | 38          | 5.6         | 100               | 0       |
| 2 | 0.315       | 58          | 8.5         | 94.5              | 5.5     |
| 3 | 0.63        | 80          | 11.8        | 86                | 14      |
| 4 | 1.25        | 116         | 17.1        | 74.2              | 25.8    |
| 5 | 2.5         | 161         | 23.7        | 57.1              | 42.9    |
| 6 | 5           | 227         | 33.4        | 33.4              | 66.6    |
| 7 | 10          | 0           | 0           | 0                 | 100     |

The expenditures of individual fractions of limestone aggregate per 1 m³ of concrete mix are shown in Table 2.

Table 2. Aggregate consumption per 1 m³ of the mixture.

| №  | Fraction (mm) | Expenditure (kg/m³) |
|----|---------------|---------------------|
| 1  | 0.16          | 85.6                |
| 2  | 0.315         | 129.1               |
| 3  | 0.63          | 180.1               |
| 4  | 1.25          | 261.1               |
| 5  | 2.5           | 362.4               |
| 6  | 5             | 511                 |

When obtaining a micro-filler, the limestone screening product was crushed in a ball mill to a specific surface area of about 500 m²/kg and added to the mixture as a substitute for the main binder in an amount of up to 50 % by weight (cement).

Analyzing the effect of precept ingredients on the creep deformations of FGCC, the method of a three-factor planning experiment of the B-D_{13} type was used for the corresponding matrix of ten options for preparing a mixture of FGCC. The input variables were x₁ - the ratio of limestone micro-filler to...
cement (%), \( x_2 \) - the ratio of SP-1 superplasticizer to cement, \( x_3 \) - the percentage of particles with a diameter 0.08 mm in the limestone micro-filler. Instantaneous deformations of 100x100x100 mm cube samples were studied as response functions. 15 samples (five of ten mixtures were specifically chosen for the creep tests) were tested-cubes of 100x100x100 mm - 3 samples for each of the five variants of the mixture composition, given in Table 3. The samples were solidified under natural conditions. The plasticity of the mixture was controlled by the spread of the standard cone. For each composition, a water-solid ratio was selected according to the spread on the shaking table, equal to 110 mm.

| № composition | binder (kg) | aggregate (kg) | cement (kg) | limestone (kg) | Superplasticizer SP-1 (kg) |
|---------------|-------------|----------------|-------------|----------------|--------------------------|
| 1             | 672         | 1528           | 672         | 0              | 6.72                     |
| 2             | 672         | 1528           | 336         | 336            | 0                        |
| 3             | 672         | 1528           | 472         | 200            | 0                        |
| 4             | 672         | 1528           | 472         | 200            | 2.11                     |
| 5             | 672         | 1528           | 553         | 119            | 4.15                     |

3. Research results and their analysis
Using the experimental planning method, the following regression equation for instantaneous deformations was obtained:

\[
y = 295.9 + 63.51x_1 - 9.3x_2 + 10.12x_3 + 378.5x_1^2 - 158.5x_2^2 - 153.2x_3^2 - 92.9x_1x_2 - 67.49x_1x_3 + 106.85x_2x_3
\]

(3)

The graphs of the relations (Figure 2) reveal the effect of the co-acting amounts of limestone and superplasticizer SP-1 in the binder part on the instantaneous deformations of the FGCC. The minimum of deformations is noted at the limestone content in the amount of 17-25 % from the mass of the binder, and at the excess of 30%, the deformations of concrete increase, reaching the limit values at the content of the superplasticizer SP-1 in the amount of 4-5 % from the mass of the solid part of the binder.

![Figure 2. Dependence of instantaneous deformations on the percentage of SP-1 superplasticizer and filler in % in the composition of FGCC Model: Y=3.1x^2-6.6x+46.7.](image)

The compositions of FGCC, for which experiments on short-term creep were carried out, are shown in Table 4. The following chart reveals the dependence of instantaneous deformations on the percentage of SP-1 superplasticizer and filler in % in the composition of FGCC.

|№ exp. | Compositions |
|-------|--------------|
| 1     | W/C=0.34, L/C=0%, SP-1=1% от Т, |
| 2     | W/C=0.45, L/C=50%, SP-1=0% от Т, |
| 3     | W/C=0.39, L/C=17.8%, SP-1=0.75% от Т, |
| 4     | W/C=0.41, L/C=50%, SP-1=0.75% от Т, |
| 5     | W/C=0.46, L/C=30%, SP-1=0.75% от Т, |

Table 4. Concrete compositions.
The composition numbers and the corresponding calculated values of the straight creep rates of concrete are presented in Table 5.

**Table 5.** Composition numbers and corresponding calculated values of straight creep rates of concrete.

| № of mixtures | Water-cement ratio | Limestone-cement ratio (%) | Superplasticizer SP-1 of Cement mass (%) | Straight creep C_{cr}(28)calc (MPa$^{-1}$) |
|---------------|---------------------|----------------------------|------------------------------------------|--------------------------------------------|
| 1             | 0.45                | 50                         | 0                                        | 7.5E-05                                   |
| 2             | 0.34                | 0                          | 1                                        | 4E-05                                     |
| 3             | 0.46                | 30                         | 0.75                                     | 7.7E-05                                   |
| 4             | 0.39                | 17.8                       | 0.75                                     | 4.2E-05                                   |
| 5             | 0.41                | 50                         | 0.75                                     | 6E-05                                     |

The composition measure and experimental values of the straight creep rates C_{τ0} and σ are given in Table 6.

**Table 6.** Composition numbers and experimental values of the straight creep rate C_{τ0}.

| № of mixtures | Straight creep rate relative to stress C_{τ0}×σ (MPa$^{-1}$) | Straight creep rate C_{τ0} (MPa$^{-1}$) |
|---------------|---------------------------------------------------------------|------------------------------------------|
| 1             | 18.8 × 10$^{-5}$                                              | 2 × 10$^{-5}$                            |
| 2             | 80 × 10$^{-5}$                                                | 5 × 10$^{-5}$                            |
| 3             | 39 × 10$^{-5}$                                                | 3 × 10$^{-5}$                            |
| 4             | 11 × 10$^{-5}$                                                | 1 × 10$^{-5}$                            |
| 5             | 37 × 10$^{-5}$                                                | 2.5 × 10$^{-5}$                          |

The composition numbers, their corresponding calculated dependences, theoretical C_{cr,teor}, and experimental C_{cr,exp}, as well as the values of the linear creep measure of concrete are given in Table 7.

**Table 7.** Composition numbers, their corresponding approximate calculated dependences, theoretical C_{cr,teor} and experimental C_{cr,exp}, and the corresponding values of the straight creep rate of concrete.

| № of mixtures | Straight creep rate, theoretical C_{cr,teor} | Straight creep rate, experimental C_{cr,exp} |
|---------------|----------------------------------------------|---------------------------------------------|
| 1             | 4 × 10$^{-5}$                                | 2.8 × 10$^{-5}$                            |
| 2             | 7.5 × 10$^{-5}$                              | 4 × 10$^{-5}$                              |
| 3             | 4.2 × 10$^{-5}$                              | 3 × 10$^{-5}$                              |
| 4             | 6 × 10$^{-5}$                                | 1 × 10$^{-5}$                              |
| 5             | 7.7 × 10$^{-5}$                              | 2.5 × 10$^{-5}$                            |

The obtained mathematical models make it possible to optimize the expenditures of the micro-filler and superplasticizer by technological and operational properties and to design concretes with a reduced level of instantaneous, short-term and long-term deformations. The minimum of instantaneous deformations is recorded when the content of the micro-filler in the concrete is about 18-22 % (Figure 2), in which a denser and more uniform composite structure is formed between the aggregate and the binder, with a viscous gel component and a rigid skeleton of the aggregate, providing improved performance characteristics of concrete, with increased crack resistance and reduced strain values. The combined use of a fine filler and a superplasticizer reveals a synergistic effect, which is caused by an improvement in the adsorption of complex additive particles on cement particles and an increase in the adhesion of aggregate, cement and additive grains during concrete hardening.

The data of the above experiments show that the fine limestone filler binds free moisture during concrete hardening, which helps to reduce the deformations of the FGCC.
4. Conclusions
The theoretical and experimental values of the linear creep measure differ significantly for the compositions of FGCC with the addition of limestone and superplasticizer tested at the age of 100 days. The presence of a fine limestone fraction affects the reduction of creep deformations. This effect is more apparent for compositions with a fine limestone component in the binder up to 30% and a superplasticizing additive Sp-1 in the amount of 0.75% of the binder. When concrete is hardened, the filler together with the SP-I superplasticizer helps to strengthen the contact zone between the cement stone and the aggregate. In this case, a stronger composite structure is formed between the filler and the binder. This reduces the level of long-term creep deformations by an average of 80%, that promotes the growth of effectiveness and enhancement of both the physical and mechanical properties of the FGCC, an increase in its early strength by an average of 30%. Future studies are viewed to research the behavior of FGCC on and with different levels of consolidating, loading, and creep strain manifestation, as well as different kinds of plasticizing agents in a complex additive.

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