Features of the fine-grained concrete physical and mechanical properties and obtaining a “\(\tau-\gamma\)” deformation curve for it based on the author’s theory

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Abstract. Fine-grained concrete has recently been increasingly used in practice for several reasons. The literature analysis shows that for the classes B15-B60 this type of concrete has lower values of strength characteristics and initial deformation modulus at a higher cement consumption compared to heavy-weight concrete. However, for high strength classes, fine-grained concrete has a higher compressive strength (for the class B100 - by 20.1%) than heavy-weight concrete. The model parameters’ (geometric, physical and kinematic) calculation according to the author’s theory of the anisotropic materials force resistance to compression by prof. B.S. Sokolov for heavy and fine-grained concrete of various classes - from B15 to B100. It has been established that the inclination angle of the shear sites \(\alpha\) with increasing concrete class increases nonlinearly, and, starting from class B60, it tends to a certain constant value: for heavy-weight concrete - 73-750, and for fine-grained concrete - 67-710. For the first time on the basis of the theory, a “\(\tau-\gamma\)” deformation curve for fine-grained concrete was obtained. It can be used in calculating bent reinforced concrete elements along an inclined section, in calculating the reinforcing bars’ anchoring length in concrete, and also in solving other practical issues.

Introduction
Fine-grained concrete has recently been increasingly used in practice, due to three main reasons [1]-[4]:

1 – the needs of the thin-walled reinforced concrete structures’ production (the so-called reinforced cement; they are made of fine-grained concrete with reinforcement from frequent woven or welded mesh of thin steel wire or composite materials), small-piece products by force pressing or vibrocompression, as well as special toppings for hardening floors;

2 – the absence of high-quality material deposits for producing coarse aggregate in many regions of the country, the delivery of which from other places at a cost exceeds the cost of cement increased consumption, which has fine-grained concrete compared to ordinary heavy-weight concrete;

3 – the needs of high-rise construction in high-strength and ultra-high-strength (Ultra-High-Performance Concrete) concrete of the classes B60-B100 and B100-B200, respectively. So, starting from a certain level of strength, coarse aggregate in ordinary heavy-weight concrete prevents a further increase in strength and therefore it is excluded from the mixture.
Thus, regardless of the strength class, fine-grained concrete is obtained - concrete with only fine aggregate made of sand. Moreover, in order to obtain ultrahigh-strength concrete, silica fume, alumina cement and superplasticizers are usually added to the mixture in redistributed percentages.

The presence of only fine aggregate in the concrete in question provides a higher uniformity of the structure, and as a result, lower properties’ variability. Unfortunately, this well-known fact has not yet been reflected in the norms for the reinforced concrete structures’ design - when assigning safety factors: for example, the material safety factors for fine-grained concrete according to BC 63.13330.2018 are taken to be the same as for heavy-weight concrete: $\gamma_b = R_{bm}/R_b = 1.3$, $\gamma_{bt} = R_{btm}/R_{bt} = 1.5$ – respectively during compression and tension.

A number of authors classify fine-grained concrete as heavy-weight concrete, for example, [5]. However, the GOST 26633-2012 name “Concrete is heavy and fine-grained. Technical conditions” suggests that this is wrong. According to GOST 25192-2012 “Concrete. Classification and general technical requirements”: heavy-weight concrete - it is cement binder concrete with dense small and large aggregates; fine-grained concrete - it is concrete on a cement binder with a dense fine aggregate. Moreover, Table 3 shows that these two types of concrete have different densities.

Materials and methods

Let us conduct a comparative analysis of the physical and mechanical properties of fine-grained and heavy-weight concrete. Based on this, we establish the features of these two types of concrete in strength calculations in general and upon receipt of the “$\tau$-$\gamma$” deformation curve in particular.

According to the Recommendations (Recommendations on the heavy and fine-grained concrete compositions selection (to GOST 27006-86). - Moscow Central Design Institute of Standard Design Gosstroy USSR, 1990. - 72 p.), Depending on the size module, sand aggregate has its own application field in the fine-grained concrete manufacture (Table. 1):

**Table 1.** The sand fineness module and its scope in the fine-grained concrete manufacture

| Fineness modulus, $M_{fn}$, mm | Grain classification | Concrete application. Strength class |
|-------------------------------|----------------------|-----------------------------------|
| From 2.5                      | large                | B30 and higher                    |
| 2.0-2.5                       | average              | B15-B30                           |
| 1.5-2.0                       | fine                 | B10-B15                           |
| 1.0-1.5                       | very fine            | B10 and below                     |

In the Manual (Manual on the design of reinforced cement structures (to Building Codes and Regulations 2.03.03-85). - M.: Stroyizdat, 1989. - 208 p.), And then also in BC 96.13330.2016 “Armored cement structures” depending on the manufacturing method and sand fineness, aggregate fine-grained concrete is divided into three groups (Table 2):

**Table 2.** Fine concrete groups

| Fineness modulus, $M_{fn}$ | Concrete hardening conditions | Concrete Group | Recommended strength class, MPa |
|---------------------------|-------------------------------|----------------|-------------------------------|
| $M_{fn}$ >2.0             | Natural or heat moisture treatment at atmospheric pressure | A              | B20-B40                       |
| 2.0 > $M_{fn}$ >1.0      | the same                      | B              | B20-B30                       |
| $M_{fn}$ >1.0            | Autoclave curing              | C              | B20-B60                       |

Moreover, for a given strength class of fine-grained concrete:
– all three groups accept the same prismatic strength, $R_b$;
– groups A and B have the same tensile strength, $R_{bt}$. 
group B tensile strength $R_{bt}$ 15–20% is lower than that of the other groups (the regularity is taken into account that with a decrease in the sand fineness modulus, concrete strength decreases);

– initial deformation modulus in fine-grained concrete ($E_{b,M}$) lower than in heavy-weight concrete ($E_{b,T}$).

If the coefficient $k = E_{b,M} / E_{b,T}$ is entered, then it is possible to calculate the following average values:

– for fine-grained concrete, group A, natural hardening: $k = 0.80$;
– for fine-grained concrete, group A, with heat-moisture treatment: $k = 0.73$;
– for fine-grained concrete, group B, natural hardening: $k = 0.73$;
– for fine-grained concrete, group B, with heat-moisture treatment: $k = 0.64$;
– for group B fine-grained concrete with autoclave curing: $k = 0.64$.

The coefficient $k$ value varies within the small limits depending on the concrete class in strength relative to its average value.

In BC 63.13330.2018, the first two groups of fine-grained concrete are combined into one - group A, and the latter is renamed to group B. At the same time, the influence of the sand size modulus $M_{fn}$ < 2.0 mm for strength is taken into account by a correction factor equal to 0.8 - the same for $R_b$ and $R_{tr}$ (earlier in the norms, the influence of this factor on $R_b$ was not taken into account). The coefficient $k$ average value is approximately the same as above.

Comparing heavy-weight and fine-grained concrete classes B15-B60, it is possible to find the following differences, which are summarized in Table.3.

**Table 3.** The difference between heavy-weight and fine-grained concrete classes B15-B60

| No. | Parameter, unit | Heavy-weight concrete | Fine concrete |
|-----|----------------|-----------------------|--------------|
| 1.  | Coarse aggregate type and density, kg/m³ | Crushed stone and gravel from dense rocks with a density of 2000-3000 kg/m³ | absent |
| 2.  | Type of fine aggregate and density, kg/m³ | Natural sand or sand from screenings of crushing rocks with a density of 2000-2800 kg/m³ | the same |
| 3.  | Maximum coarse aggregate size, mm | 10-120 | absent |
| 4.  | Fine aggregate fineness modulus, mm | 1.5-3.5 | the same |
| 5.  | The average density of concrete, kg/m³ | 2200-2500 | 1800-2200 |
| 6.  | Maximum Recommended Cement Consumption, kg/m³ | 550 | 750 |
| 7.  | Compressive Strength Class, MPa | B3.5-B100 | Group A: B3.5-B40 Group B: B15-B60 |
| 8.  | Minimum concrete strength class for load-bearing structures, MPa | B15 | B20 |
| 9.  | The ratio of the elastic modulus of this type of concrete to the value of the module for heavy-weight concrete | 1.0 | Group A natural hard 0.8 Group A thermal treatment 0.73 Group B 0.64 |
| 10. | The compressive strength ratio (calculated or normative) of a given concrete to the strength | 1.0 | $M_{fn}$ > 2.0 mm: 1.0 $M_{fn}$ < 2.0 mm: 0.8 |
value for heavy-weight concrete

|   |   |   |
|---|---|---|
| 11. The ratio of tensile strength (calculated or normative) of a given concrete to the value of strength for heavy-weight concrete | 1.0 | 
|   |   | 
|   |   | 
| 12. Parametric points of concrete deformation diagram: | 0.0020 | the same |
|   |   | 
|   |   | 
| 13. Minimum length of anchor reinforcement in the stretched zone | 15ds | Group A: 25ds |
|   |   | \ Group B: 15ds |

**Notes:**

1 – indicator values are adopted in accordance with GOST 26633-2012 “Heavy and fine-grained concrete”;

2 – in accordance with BC 63.13330.2018 “Concrete and reinforced concrete structures”;

3 – with a short load.

Further, the figures show a comparison of the physical and mechanical properties of fine-grained and heavy-weight concrete of various classes according to BC 63.13330.2018 (from B10 to B100). The jumps on the curves constructed for fine-grained concrete on these graphs after B40 class are obtained due to the group A change (B10-B40 classes) to group B (B40-B60 classes).

**Figure 1.** Concrete strength dependence on the class: 1, 2 – Rbn and Rb for heavy-weight concrete; 3, 4 – Rbn and Rb for fine-grained concrete
Figure 2. Concrete strength dependence on the class: 1, 2 – $R_{bn}$ and $R_{bt}$ for heavy-weight concrete; 3, 4 – $R_{bn}$ and $R_{bt}$ for fine-grained concrete.

Figure 3. The concrete deformation modulus dependence $E_b$ on the class: 1 – for heavy-weight concrete; 2 – for fine-grained concrete.

Figure 4. Strength Relationship of heavy-weight concrete in compression and tension: 1 – $R_{bn} / R_{bt}$, 2 – $R_b / R_{bt}$. 


Figure 5. Strength Relationship of fine-grained concrete in compression and tension: $1 - R_{bn} / R_{bmn}$, $1 - R_{bt} / R_{btr}$

As it can be seen from the previous data, fine-grained concrete of B10-B60 classes has lower values of strength characteristics and initial deformation modulus at a higher cement consumption in comparison with heavy-weight concrete. This requires a thorough feasibility study before applying the type of concrete under study at construction sites. There are not so many cases in which it is expedient to use it:

1) when it is required to produce thin-walled reinforced concrete structures, small-piece products by force pressing or vibrocompression, as well as hardening concrete floors with special toppings;

2) when there is suitable sand for this in the area of concrete production, but there is no quality material to obtain large aggregate and its delivery from other places is economically unprofitable;

3) when it is required to obtain high-strength and ultra-high-strength concrete, and large aggregate, starting from a certain level of strength, prevents this.

Let us consider the last case of this article in more detail. Modern research results in the field of high-strength fine-grained concrete (HSFC) and the calculation are presented in [6,7]. They study the following composition: Portland cement grade PC 500 DON $- 900$ kg/m³; washed quartz sand, class 1 with fineness modulus $M_{fp} = 2.5-2.8$ mm $- 860$ kg/m³; organic mineral modifier MB 3-50K (as an active microfiller) $- 360$ kg/m³; water $- 190$ kg/m³.

The prisms $10 \times 10 \times 40$ cm in size were made from this composition to determine prism strength ($R_b$), initial strain modulus under axial compression ($E_b$) and tensile strength in bending ($R_{bt}$), as well as the samples - eights with a section of $7 \times 7$ cm for determining axial tensile strength ($R_{bt}$). Three samples were provided for each type of loading. To determine cubic strength ($R$), 6 samples of cubes $10 \times 10 \times 10$ cm in size were concreted.

**Discussions and Results**

Table 4 shows the experiment results in the first line [6].

| Event | $\gamma$, kg/m³ | Axial compression | Axial extension | Bending tensile |
|-------|----------------|-------------------|----------------|----------------|
|       | $R$, MPa | $R_b$, MPa | $R_b / R_t$ | $E_b$, MPa | $\mu_b$ | $R_{bt}$, MPa | $\varepsilon_{bt0}$ | $R_{bt0}$, MPa | $\varepsilon_{bt0}$ |
Unfortunately, according to the notation given in this paper, it is not immediately clear what concrete class is involved: whether it is about B127 if we assume that when calculating cubic strength $R$ and other indicators, the reliability coefficient associated with the variability of concrete properties and probabilistic student distribution indicators has already been taken into account; or about B100, as stated later in the text of the article itself, then it should be considered that Table 4 in its first row does not give the calculated values, but in the averaged experimental values: $R_m, R_{bm}, R_{btm}, R_{btfm}, E_{bm}$ etc. We assume that the second event is true. Then the reliability coefficient for the concrete in question is equal to

$$\gamma_m = \frac{R}{R_m} = \frac{100}{127.3} = 0.786.$$  

The remaining calculated values are given in the second row of Table 4 (when calculating them, the reliability coefficients for concrete under compression and tension are taken into account, respectively $\gamma_b = R_{bm}/R_b = 1.3$, $\gamma_{bt} = R_{btm}/R_{bt} = 1.5$, as well as a reduction factor of the working condition $\gamma_{b,br} = (360 - B)/300 = (360 - 100)/300 = 0.867$, taking into account the increase in high-strength concrete fragility).

For comparison, the 3rd line shows the calculated data for high-strength heavy-weight concrete (HSHC) of the same class B100. It can be seen that the HSFC design strength is 20.1% more compressive and the tensile strength 6.3% less (or approximately the same) than of HSHC. Thus, some advantages of HSFC are found in comparison with HSHC.

In addition, it should be noted that the strength ratio $R_d/R_{br}$ for different classes - from B15 to B60 - it is the same both for fine-grained concrete and for heavy-weight concrete. However, for the B100 class there is a difference: for the HSFC base – $R_d/R_{br} = 27.56$; for HSHC – $R_d/R_{br} = 21.59$ (in the first case on 27.6% this ratio is bigger).

As it is known from the force resistance theory of anisotropic materials to compression by prof. B.S. Sokolov [8.9] the ratio $R_d/R_{br}$ is decisive in calculating the inclination angle $\alpha$ of the sliding platforms - the wedge side faces, which is formed under a stamp acting on a compressed concrete or reinforced concrete element (the calculated model of a compressed element according to the theory is shown below in Figure 8):

$$\alpha = \arctg \left( 0.25 \frac{R_b}{R_{bt}} - 1.56 \right)$$  \hspace{1cm} (1)

According to this formula in Figure 6 a dependence graph of the angle $\alpha$ on the concrete class for strength (based on the data of BC 63.13330.2018 and [6]).
Figure 6. Dependence of the angle \( \alpha \) on the concrete class: 1 – heavy-weight concrete, 2 - fine-grained concrete up to B60 class; 3 - the distribution area boundary of fine-grained concrete according to BC 63.13330.2018; 4 - angle value for class B100 HSFC [6]; 5 - theoretical values of the angles \( \alpha \) for B60-B100 HSFC classes, obtained by the formula (1) and the experimental ratio \( R_b/R_{bt} = 27.56 \); 6 – Experimentally determined value of \( \alpha \) for B100 class HSFC

Figure 6 shows that with an increase in the concrete class this angle also increases according to the nonlinear law, and for HSHC it tends to some constant value \( \alpha \approx 73-75^0 \), but for Navy this trend is not observed.

Figure 7 shows the photographs with diagrams of the different classes concrete samples’ destruction which indicate that the inclination angle of the wedge in the compaction zone for B20 class heavy-weight concrete [9] is approximately 58°, for high-strength heavy-weight concrete B100 [10] – 75°, and for high-strength fine-grained concrete [6] – 67°, which confirms the reliability of formula (1) in the first two cases, and for the case of BMD this formula should be adjusted as follows:

\[
\alpha = \arctg \left( 0.25 \frac{R_b}{R_{bt}} - 4.53 \right)
\]

(2)

To clarify this dependence, it is necessary to conduct several series of cubes and prisms tests for compression and eights - for tensile stresses for B60-B100 classes HSFC.
Figure 7. The destruction scheme of cylinder samples 150 × 300 from B20 class heavy-weight concrete [9] (a) and B100 [10] (b) and cube samples of B100 high-strength fine-grained concrete (c) [6]

As it can be seen from Figure 8, with a change in the angle $\alpha$, the geometric parameters of the calculation model also change, which determines a different mechanism for the elements’ destruction of heavy and fine-grained concrete classes B60-B100. At the same time, for high-strength concrete, the specific share of compression resistance in a compressed-stretched core is greater than that of low-strength concrete. And vice versa: the specific share of tensile and shear resistance is smaller, and this is the reason for the more brittle fracture of high-strength concrete - both HSHC and HSFC.

Figure 8. Geometrical and static parameters of the design model depending on the concrete class

Earlier in [11] for heavy-weight concrete, based on the author’s theory [8,9] and three-line tensile-compression diagrams according to BC 63.13330.2018, a concrete deformation curve “$\tau$-$\gamma$” was obtained. In this article, we will build it for a HSFC class B100, which will be done for the first time. The basis for this is the HSFC deformation curves of the under uniaxial compression and tension, obtained by the known formulas of the set of rules. They are presented in Figure 9.

Figure 9. Design HSFC deformation curves under uniaxial compression (a) and tension (b), constructed according to BC 63.13330.2018
The formulas for determining the parametric points of “τ-γ” chart in accordance with [11]:

\[
\gamma_{\beta_1} = \frac{(\varepsilon_{\beta_1} - 0.5k_2\varepsilon_{\sigma_0}\cot\alpha)}{0.4k_2}, \quad \tau_{\beta_1} = 0.4E_p\gamma_{\beta_1},
\]

(3)

\[
\gamma_{\beta_0} = \frac{\varepsilon_{\beta_0}\sin\alpha}{0.4k_2}, \quad \tau_{\beta_0} = R_{\beta},
\]

(4)

\[
\gamma_{\beta_2} \approx \frac{\varepsilon_{\beta_2}\sin\alpha}{0.4k_2}, \quad \tau_{\beta_2} = \tau_{\beta_0} = R_{\beta}.
\]

(5)

where \(k_1 = A_0/(A - A_f)\), \(k_2 = 2A_{sh}/(A - A_f)\), \(A_0\), \(A_{sh}\), \(A_f\) – are the areas of tension, shear and crushing (compression) - see Fig. 8.

The HSFC deformation curve of class B100 during shear is shown in Figure 10.

![Figure 10. The HSFC deformation curve shear class B100](image)

On the whole, the result obtained does not contradict the previous studies [11] and can be used in calculating bending reinforced concrete elements with an inclined section, in calculating the reinforcing bars’ anchoring length in this concrete, and also in solving other practical issues.

Summary

1. An analysis of the fine-grained concrete strength and deformation characteristics, which differs from ordinary heavy-weight concrete, is as follows: for the classes B15-B60 it has lower values of strength characteristics and the initial deformation modulus at a higher cement consumption. However, for high strength classes, fine-grained concrete has a higher compressive strength (for class B100 - by 20.1%) than heavy-weight concrete.

2. The model parameters’ (geometric, physical and kinematic) calculation according to the author’s theory of concrete compressive strength for heavy-weight and fine-grained concrete of various classes - from B15 to B100. It has been established that the angle \(\alpha\) with an increase in the concrete class increases according to the nonlinear law, and, starting from class B60, it tends to a certain constant value: for heavy-weight concrete – 73-75°, and for fine-grained concrete – 67-71°. At the same time, for high-strength fine-grained concrete of B60-B100 classes, based on the data of [6], the correlation for the angle \(\alpha\) was made.

3. For the first time, a deformation curve of fine-grained concrete was obtained, which can be used in calculating the bending reinforced concrete elements by an inclined section, in calculating the reinforcing bars’ anchoring length in this concrete, and also in solving other practical issues.
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