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Layer model of elasticity modulus prediction for lightweight concretes

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Abstract. Reducing the structures' weight is one of the basic approaches to improving the efficiency of construction. There are many developments in this area, especially with lightweight concretes. One of the problems for structural lightweight concrete is a fairly low modulus of elasticity and increased plastic deformations in extreme conditions due to the high porosity of the lightweight aggregates. Therefore, the assessment and prediction of the deformative properties of lightweight concretes is an urgent scientific task on a par with heavy concretes. Our previous work proved the performance of the layer calculation model for heavy concretes. In this research, we attempted to test the layer model when calculating the deformative properties of concretes containinglightweight aggregates.

1. Introduction

Developing a calculation model of the heavy concretes deformative properties, the dependence of the elastic modulus on the layer model with the number of layers $i=n$, the elastic modulus of the layer E_i and the relative thickness of the layer δ_i was proposed

$$E_c = \frac{E_1 E_2 \dots E_n}{\sum_1^n \delta_i \frac{E_1 \dots E_n}{E_i}}. \quad (1)$$

Consideration of the graphic dependence of the heavy concrete elastic modulus with strength class B25 (Fig. 1) allows us to assess the non-additivity of the elastic modulus of concrete.It depends on the moduli of structural layers and the fundamentally high importance of both the elastic modulus of the aggregate and the elastic modulus of the contact zone "cement paste-aggregate" (ITZ) in the formation of the composite structure modulus. As seen in Fig.1 modulus calculated as the weighted average of the modulus of the layers is significantly higher than the actual one, which indicates that a decrease or increase in the elastic modulus of one of the layers leads to a disproportionate decrease or increase in the modulus of the entire structure. Therefore, the low modulus of elasticity of porous light aggregates leads to an intense decrease the modulus of elasticity of structural concrete. For example, the elastic modulus of heavyconcrete class B15 is about $2.3 \cdot 10^4$ MPa, and the elastic modulus of light concrete D1600 of the same class B15 is $1.4 \cdot 10^4$ MPa.

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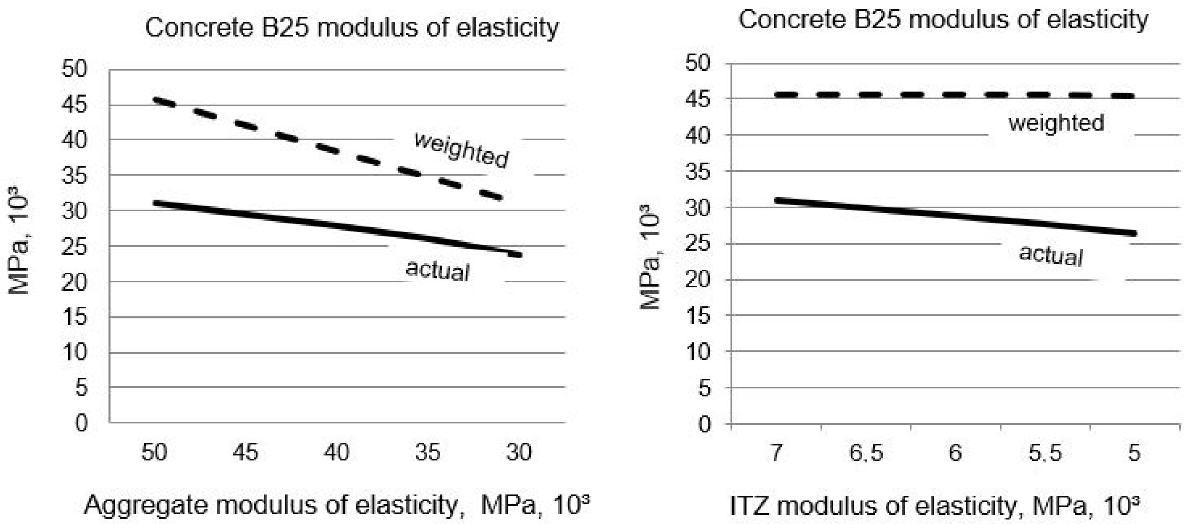

Figure 1. Relations of the concrete B25 elastic modulus to the elastic modulus of layers.

In heavy concretes, hydrated cement paste [1–2], aggregate [3–6], and the contact zone between them were used as layers [6–8]. In concretes with lightweight aggregate, at the initial stage of the hardening process, capillary pumping out the closing water from the binder layer, the structure of the cement hydrated paste in the layer and the contact zone is compact due to the above effect [9–12]. This is confirmed by the features of deformation under a load of heavy concretes in comparison with light ones on porous aggregates. If heavy concretes have significant plastic deformations when sustained at loading stages, then concretes on porous aggregates have almost no such plastic deformations [13–21]. As shown in previous studies, the main cause of plastic deformation of heavy concrete when withstood at loading stages is increased porosity and deformability of the cement hydrated paste and aggregate contact zone ITZ. Self-sealing of the contact zone with a light aggregate, leads to the absence of such plastic deformations.

In this regard, and connection with the different density and, as a consequence, the different modulus of small and large aggregates in the calculated layer model of concrete on a light aggregate, we propose to consider cement hydrated paste, fine and coarse aggregates as layers (Fig. 2).

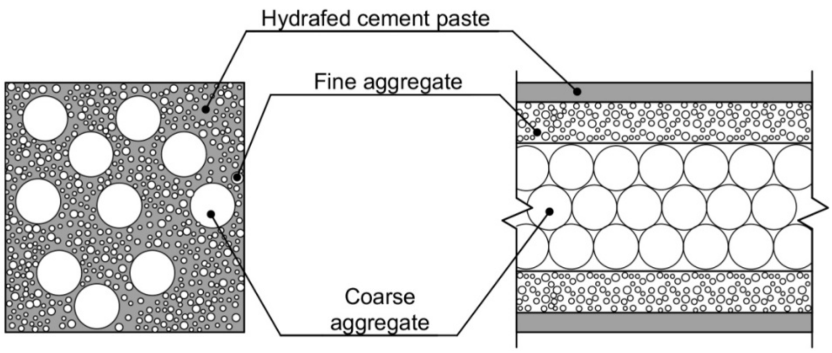

Figure 2. Calculated layer model of concrete deformability on a light aggregate.

A special feature of light concretes can be the use of both lightweightaggregate, and a combination of heavy and light aggregates, often fine heavy and coarse light. In the case of a combination of heavy and light aggregates, it is theoretically necessary to evaluate the modulus of the mortar part using the heavy concrete model, followed by an additional calculation using the two-layer "mortar–coarse aggregate"model. At the same time, it is possible to assume that in the process of pumping out the mix`s water with a coarse light aggregate, the contact zone ITZ in the heavy mortar part is also compacted and its influence on the module is disappeared. Therefore, we will test the proposed model "cement hydrated paste–aggregate1–aggregate2".

2. Materials and Methods

The analytical method was used to select and evaluate the composites layer model calculation method.

Standard methods of Russian State Standards GOST 24452-80 “Concretes. Methods of prismatic, compressive strength, modulus of elasticity and Poisson's ratio determination” and GOST 22690-2015

“Concretes. Determination of strength by mechanical methods of nondestructive testing”were used to determine the modulus of elasticity and compressive strength of concrete of various classes. Each classes series of 3 samples were tested under compression on the Matest press with determination of longitudinal elastic and plastic deformation using digital deformation sencors on every sides of sample. Compression was made by 10 % of cracking stress stages to the 40 % of cracking stress (Fig.2). The elasticity modulus has been determined as a relation of 30 % cracking stress to the sum of elastic relative deformation except plastic on stages delay by standard. Compressive strength was determined on 6 samples series by standard.

To define the fact concrete elasticity modulusin our experiment, we used local producers’ materials:

1. The keramzite gravel with an elastic modulus of E_{ag2}=5*10^3 MPa;

2. The perlite sand with the E_{ag1}=7*10^3 MPa;

3. The granite coarse aggregate and quartz sand with a strength of R_{agg}=1000 MPa and an elastic modulus of E_{ag1}=50*10^3 MPa;

4. The Portland cement B42.5 CEM I with a water requirement of normal density of 25 % and the compressive strength of hydrated cement paste with W/C of normal density in standard age R_{cem}=100 MPa and an elastic modulus of E_{cem}=50*10^3 MPa;

5. The Portland cement B27.5 CEM III with a water requirement of normal density of 27 % and the compressive strength of hydrated cement paste with W/C of normal density in standard age R_{cem}=700 MPa and an elastic modulus of E_{cem}=30*10^3 MPa.

The contents of various classes mixture components are presented in Table 1.

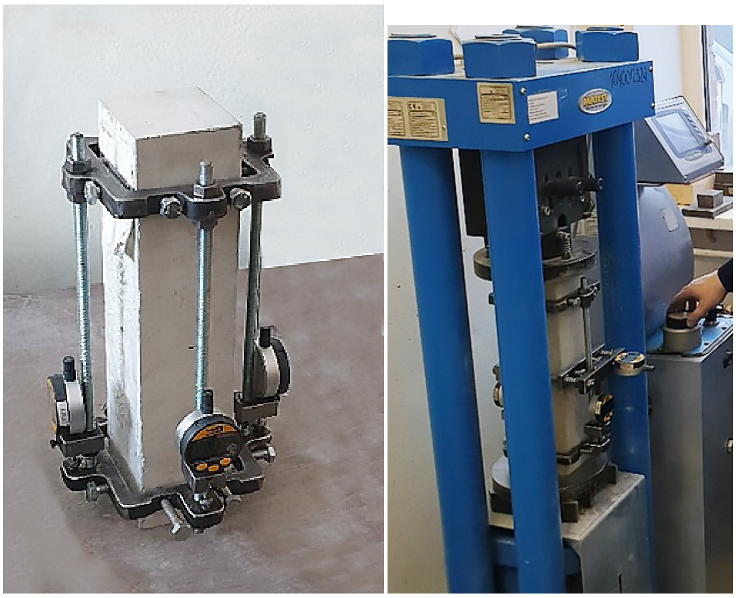

Figure 3. Concrete sample modulus of elasticity under compression testing.

3. Results and Discussion

Existing calculations of lightweight concrete elasticity modulus by M.Z Simonov, G.D. Zhiskrely, O.Y. Berg, A.L. Ambartsumyan and others used as a factors: concrete strength, aggregate elasticity modulus, average density, but not all components modulus together. It makes difficult to use these equation for modulus definition depending on mix components containing. Our calculation is determining the relative thicknesses of layers in first case, and these factors are most important in elasticity forming.

According to the proposed calculation model [22], the light concrete elastic modulus equation is

$$E_c = \frac{E_{cem}E_{ag1}E_{ag2}}{cemE_{ag1}E_{ag2} + ag1E_{cem}E_{ag2} + ag2E_{cem}E_{ag1}}, \quad (2)$$

E_{cem} is the modulus of elasticity of the cement hydrated paste layer;

E_{ag1} is the modulus of elasticity of the layer "fine aggregate";

E_{ag2} is theelastic modulus of the layer "coarse aggregate";

cem, $ag1$, $ag2$ are the relative thickness of the layers of cement, fine and coarse aggregates.

The relative thicknesses are determined from the condition of surface areas in the contact zones between the layers S_{itz} with the thicknesses δequality

$$cem = \frac{\delta_{cem}}{\delta_{mv}} = \frac{S_{its}\delta_{cem}}{S_{its}\left(\delta_{cem} + \delta_{agg}\right)} = \frac{V_{cem}}{V_{cem} + V_{agg}} = \frac{V_{cem}}{V_c}, \quad (3)$$

V_{cem} is a volume of cement paste;

V_c is a volume of concrete.

The relative thickness of the aggregate layers is determined by the same principle

$$ag1 = \frac{V_{ag1}}{V_c};$$

$$ag2 = \frac{V_{ag2}}{V_c}.$$

For testing the model lightweight concrete was produced in different versions:

1. Coarse aggregate is the keramzite gravel, fine aggregate is the quartz sand;

2. Coarse aggregate is the keramzite gravel, fine aggregate is the perlite sandwitnPotland cement B42,5 and B27,5;

3. Coarse aggregate is the granite,fine aggregate is the perlite sand.

Working compositions of light concrete mixes of our own concrete mixing plant of classes B5…B15, D800…D1600 were used for testing. Table 1 shows data for the sequential calculation of the elastic modulus of light concretes by the layer model based on the parameters of the modulus of components and composition of the light concrete mix-relative thicknesses cem, $ag1$, $ag2$. To assess the accuracy, the standard values of the elastic modulus for classes according toRussian Building Norms SNiP 2.03.01-84*(1996) “Concrete and reinforced concrete structures” were used.

Table 1. Calculated and standard characteristics of the lightweight concrete elastic modulus.

$Ag1$	B	D	E_{cem}, MPa, 10^3	E_{ag1}, MPa, 10^3	E_{ag2}, MPa, 10^3	C, kg/m^3	$Ag1$, kg/m^3	$Ag2$, kg/m^3	cem	$Ag1$	$Ag2$	E_c, MPa, 10^3	E_{st}, MPa, 10^3	E_{fact}, MPa, 10^3
Quartz	7,5	1200	50	40	5	330	650	250	0.18	0.32	0.50	8.9	8.7	9.0
	10	1400				360	720	210	0.24	0.35	0.41	10.5	11.0	10.9
	15	1600				540	940	100	0.28	0.45	0.27	14.1	14.0	15.1
Perlite	5	800	50	7	5	440	55	110	0.15	0.65	0.20	7.3	6.3	6.9
	7,5	1000				520	50	130	0.18	0.60	0.22	7.5	7.2	7.5
	10	1200				880	35	165	0.30	0.40	0.30	8.8	9.5	9.0
Perlite/ PC B27.5	5	1000	30	7	5	520	50	130	0.18	0.60	0.22	7.4	7.2	7.2
Perlite/ Granite	10	1400	30	7	50	540	55	510	0.18	0.65	0.17	10.0	11.0	9.5

As can be seen from the data in Table 1, the method provides good convergence in predicting the modulus of elasticity, calculated and actual values difference is not more than 15 %.

It is noticeable that with equal density classes, the moduli of elasticity of concretes on heavyand lightfine aggregates with the very different elasticity moduliare the same but strength of perlite concrete is higher.It causes due to the greater relative thickness of the layer of the most modular component that is cement hydrated paste.

If, in order to economical efficiency, a part of the cement is replaced with micro additives, the subsequent decrease in the activity and elastic modulus of this cement hydrated paste slightly affects the light concrete elastic modulus. In this case, the more significant factor is the thickness of the cement hydrated paste layer. As can be seen from the dependence (Fig. 4) of lightweight concretes elastic modulus on hydrated cement paste elasticity modulus, even over 50 % decrease of cement paste modulus result in less than 10 % modulus decrease.

The task of structural lightweight concrete D1400…D1800 producing can be equally achieved by using of heavy fine/light coarse and light fine/heavy coarse aggregates. Second version surprisely provided homogeneous structure of concrete. This method realizing made possible to test additively layer model, but also it’s useful in technology. Method’s choose depends on composition’s economical parameters.

Providing and improving the deformative properties of structurallightweight concrete can result in characteristics close to the levels of heavy concrete. With the slightly lower level of the elasticity modulus (15…18*10^3 MPa) plastic deformations of lightweight concrete under prolonged loading are much less, and the weight of structures can be reduced by 30…50 % and more with a significant economic effect on the level of the entire building or structure.

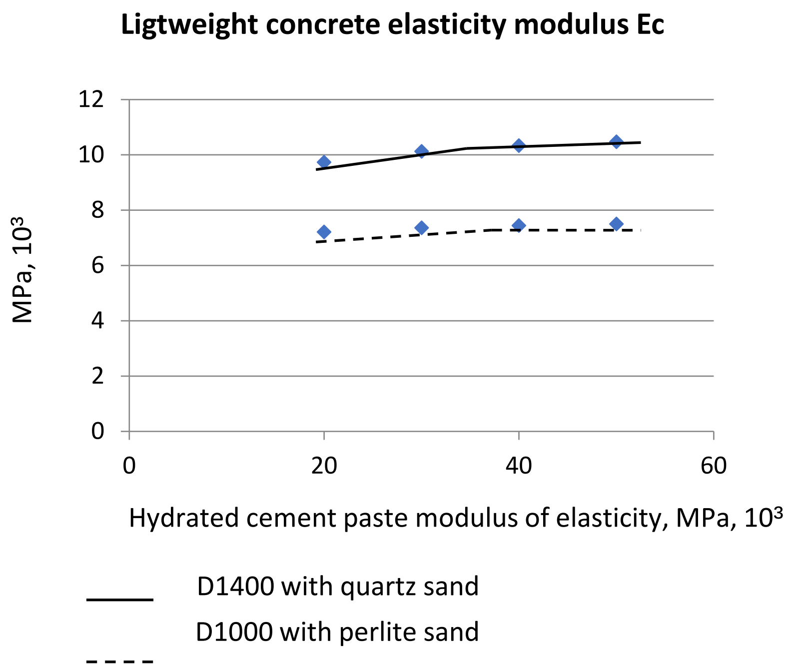

Figure 4. Lightweight elasticity modulus relation in cement hydrated paste elasticity modulus.

Analysis of the layer model result in principles of lightweight concrete elasticity modulusregulation:

1.The thickness of the layer of the binder component with the lowest content in the structure is of greater significance in the lightweight concrete deformation properties than the activity and modulus of its elasticity. It makes a great reserve of cement saving by cement class decreasing with elasticity level providing. Thus to increase the elastic modulus of lightweight concrete more efficiently increase the consumption of cement while reducing its activity and cost than increasing cement’s activity.

2.Elastic modulus of aggregates, components with the highest content in light concrete, are determining for the concrete modulus of elasticity.And compositioning of light and heavy fine and coarse aggregates provides great possibilities for lightweight concrete modulus of elasticity regulation and providing.

4. Conclusion

As a result of analytical and experimental work, the suitability of the layer model for estimating the elastic modulus of lightweight cement composites was confirmed. The calculation model based on the layer model operates on 6 factors: elastic modules and relative thicknesses of the structural layers "cement hydrated paste", "fine aggregate","coarse aggregate".

On the base of this model received the method of lightweight cement composites elasticity modulus calculation depending on mix components properties and containing. The method allows to solve two basic technological problems: 1) to ensure the normative deformability of the given density class concrete; 2) to identify ways to increase elastic properties within a given composition and raw materials.

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