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CALCULATION METHOD FOR THE FORMATION OF MICROCRACKS TAKING INTO ACCOUNT THE DENSITY OF CLAYDITE CONCRETE

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Statement of the problem. An important aspect of concrete behaviour under loading is the formation and development of microcracks. The existing methods for the calculation of values of the limits of microcrack formation for lightweight aggregate concrete do not provide sufficient convergence with the experimental data. In this regard, it is advisable to derive new formulas applicable for lightweight aggregate concrete.

Results. The paper presents the test results on concrete of different strength and density classes. It also suggests new formulas for the calculation of the limits of micro- and macrocrack formation. According to the obtained research results, an empirical coefficient is introduced based on the density class of lightweight aggregate concrete.

Conclusions. The calculation method of the upper and lower limits of microcrack formation for lightweight aggregate concrete of various strength and density classes is proposed. The method is harmonised with the provisions of the Eurocode 2. At the same time, good convergence with the experimental data is provided.

Keywords: lightweight aggregate concrete, claydite, limits of microcrack formation, density, density class.

Introduction. The use of construction and heat insulation lightweight concrete is becoming increasingly common in construction. Apart from good heat insulation properties, this type of concrete has a sufficient fire resistance [10]. Therefore it is of a lot of importance these days to develop relevant theories for calculating and designing load-bearing structures made of light concrete.

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The main feature of light concrete based on porous fillers is that it is almost impossible to design precise compositions of a concrete mix as strength and deformative characteristics of porous fillers vary significantly and thus the strength of concrete using different fillers will range considerably as well [13, 15]. Therefore the strength of concrete and its density will not be directly dependent on one another, i.e. for lower densities a higher axial compressive strength can be obtained as a result of using other fillers or additives [13]. Note that in order to obtain a construction lightweight concrete as a fine filler dense sand (river, silica or pit) but not porous one (e.g., claydite sand) is used. It is because the use of a fine porous filler causes a significant reduction in the concrete strength [6, 13, 14, 16].

One of the parameters that characterizes the operation of concrete under load is formation and development of microcracks. Particularly, it is very important to determine the upper boundary of microcrack formation (a so-called critical loading level) as its increase suggests that the third stage of the stress-strain has started (the destruction stage). This means that not only has a strength limit been reached and other operational characteristics have degraded but that there has been a change in some other parameters as well. E.g., in [19] it is shown that chloride resistance decreases dramatically as a critical level is reached.

The boundaries of micro- and macrocracks in lightweight concrete on any fillers are significantly higher than in normal density concrete [12, 13, 17]. The higher the porosity is, the higher the boundary of microcrack formation is [1]. There are some reasons for that. The cohesion of a cement matrix with a large porous filler is a lot higher than that with a dense one as there is no clear boundary between the filler and cement rock [13, 14, 16, 18] as seen in the photos taken with an electronic microscope [13, 18]. The first microcracks are generally formed along the contact of a large filler and cement matrix [24]. In [21, 23] it is also noted that around grains of a large filler the porosity of a cement rock is smaller compared to regular concrete due to a high water absorption resulting in cement rocks of lightweight concrete having a higher strength and durability than those in heavyweight ones.

Determining limits of microcracking (the lower and upper ones) is based on empirical dependencies and a system of particular coordinates allowing for various parameters. Traditionally for regular concrete formulas using a common logarithm set forth by O. Ya. Berg [2] are used that came under a lot of criticism in scientific literature as they are only applicable for concrete with dense medium-strength fillers [1, 3, 4, 7]. In [7] dependencies using exponents are suggested while [11] presents a finite element method for large-scale modeling of microcracking and concrete failure. In [22] it is noted that in order to determine when the first cracks are going to appear in ferroconcrete beams made of any lightweight concrete, most existing calculation methods do not yield a correct results and a correction coefficient has thus to be introduced.

1. Objectives and tasks. The objective of the research is to develop a calculation method for relative loads that correspond with the lower and upper limits of microcracking for claydite concrete made of a local raw material.

The objectives of the study are to consider the influence of the density of claydite concrete on the ranges of limits of microcracking and to provide their accordance with *Eurocode* 2.

2. Characteristics of the experimental samples. In order to prepare the experimental samples in the form of cubes, prisms and cylinders local materials were employed:

— claydite gravel with the fraction of 5—10 mm with the apparent density of 382 kg/m^3, relative strength in the cylinder 2.68 MPa (manufacturer — Ltd. “Claydite Gravel Plant”, Novolukoml);

— claydite gravel with the fraction of 10—20 mm with the apparent density 326 kg/m^3, relative density in the cylinder 1.86 MPa (manufacturer — Ltd. “Claydite Gravel Plant”, Novolukoml);

— claydite crushed stone with the fraction 5—10 mm with the apparent density 585 kg/m^3, relative strength in the cylinder 10.26 MPa (manufacturer — Petrikovsky Claydite Plant Ltd. “Gomel Integrated House-Building Factory”);

— claydite sand with the fraction of 0—4 mm with the apparent density 432 kg/m^3, relative density in the cylinder 4.58 MPa (manufacturer — Ltd. “Claydite Gravel Plant”, Novolukoml);

— natural pit sand with the apparent density 1580 kg/m^3;

— M500 Portland cement with the activity 49.0 MPa, with the normal density index of 25—28 % (manufacturer — Ltd. “Belorussian Cement Plant”).

The composition of the claydite concrete mixes was selected according to [8].

The composition of the concrete mix is detailed in Table 1.

The concrete mix was prepared manually in a laboratory setting. Inventory metal assembly-disassembly forms were utilized for making the samples. The experimental samples were stored in natural temperature and humidity conditions of solidification (t = 20 ± 2 °C, humidity is 90—95 %). The samples were covered with a bagging fabric and were regularly moisturized for 7 days.

Table 1

Characteristics of the experimental claydite concrete samples

Concrete type		Characteristics of the material*		Composition of a concrete mix		Density of claydite concrete at the age of 28 days, ρ^{om}, kg/m^3	Density type according to EN 1992 and calculation density ρ
Predicted	Actual	Large filler	Fine filler	Cement: Sand: Gravel (Crushed stone)	Binder/ Cement		
LC 8/10	LC 8.4/10.3	Claydite gravel with the fraction 5—10 and 10—20 mm	Claydite sand with the fraction 0—4 mm	1:0.52:1.05	0.63	950	Class 1.0 ρ = 1050 kg/m^3
LC 10/12	LC 9.9/11.8	Claydite gravel with the fraction 10—20 mm	Silica sand with the fineness modulus 1.8	1:2.41:1.37	0.51	1390	Class 1.4 ρ = 1450 kg/m^3
LC 16/18	LC 16.2/20.6	Claydite gravel with the fraction 5—10 mm and 10—20 mm	Silica sand with the fineness modulus 1.8	1:1.84:0.79	0.46	1545	Class 1.4 ρ = 1450 kg/m^3
LC 25/28	LC 23.7/29.5	Claydite crushed stone with the fraction 5—10 mm	Silica sand with the fineness modulus 1.8	1:1.89:0.74	0.42	1760	Class 1.8 ρ = 1850 kg/m^3
LC 30/33	LC 29.0/33.6	Claydite crushed stone with the fraction 5—10 mm	Silica sand with the fineness modulus 1.8	1:1.84:0.79	0.40	1780	Class 1.8 ρ = 1850 kg/m^3

Note: *binder is Portland cement M500.

3. Determining the limits for microcracking. The limits for microcracking for the experimental samples were determined using the graph method according to the results of the experiments.

The lower level of microcracking η^0_{crc} is determined by the second derivative from the dependence “loading level — Poisson coefficient”. The upper level of microcracking η^v_{crc} (level corresponding with macrocracks) is identified by means of designing the dependence “strain level — volumetric deformation) using the averaged experimental data.

The relative microcracking limits (the lower and upper one) can be given by the formulas (1), (2) respectively [9, 20]:

$$\eta^0_{crc} = 0.33k_{crc} \cdot \ln\frac{f_c}{f_{c,0}} - 0.15; \quad (1)$$

$$\eta^v_{crc} = 0.33k_{crc} \cdot \ln\frac{f_c}{f_{c,0}} + 0.1, \quad (2)$$

where f_c is the strength of concrete, MPa; $f_{c,0}$ is a value of the concrete strength, $f_{c,0} = 1$ MPa.

In [9, 20] it was experimentally found that the ratio $\eta^0_{crc}/\eta^v_{crc}$ for concrete of each type remains stable (i.e. changes in a small range) and for the above types of concrete it can be assumed that:

— $\eta^0_{crc}/\eta^v_{crc} \approx 0.67$ for normal density concrete on dense fillers;

— $\eta^0_{crc}/\eta^v_{crc} \approx 0.70$ for steel fibre concrete;

— $\eta^0_{crc}/\eta^v_{crc} \approx 0.73$ for concrete using metallurgical slag as a fine filler (metallurgical slag concrete);

— $\eta^0_{crc}/\eta^v_{crc} \approx 0.60$ for claydite concrete.

The empirical coefficient k_{crc} was introduced which is based on the value of $\eta^0_{crc}/\eta^v_{crc}$ and can be used for designing and testing of concrete and ferroconcrete structures:

$$k_{crc} = k_{c1} \cdot \frac{\eta^0_{crc}}{\eta^V_{crc}}. \quad (3)$$

In [20] it is noted that for normal concrete, steel fibre concrete, metallurgic slag concrete the coefficient $k_{c1} \approx 1$ and for claydite concrete $k_{c1} \approx 1.2$. I.e. for claydite concrete $k_{crc} \approx 0.72$.

However, as was previously shown, for lightweight concrete overall and claydite concrete in particular, the following is typical [13, 14]: for the same strength the density of a concrete matrix the applications might be fundamentally different due to the use of different fillers. Therefore the coefficient k_{c1} should be accepted considering the density of a material and once there is enough amount of correct experimental data, a formula for analytical calculations should be deduced.

According to the EN 1992 [5], the density of lightweight concrete is considered with the parameter (ρ/2200) where ρ is a calculation density of lightweight concrete accepted based on the density class [5, Table 11.1]. This parameter is actually a relative upper limit of the density of lightweight concrete of a corresponding class.

Based on the experimental data using the method of linear approximation, the dependence for calculating the coefficient k_{c1} depending on the parameter (ρ/2200) was introduced:

$$k_{c1} = 2.075 - 1.1 \cdot \frac{\rho}{2200}, \tag{4}$$

where ρ is in kg/m^3.

4. Comparison of the experimental and calculation data. Table 2 shows the comparison of the experimental and calculation values of relative limits of microcracking of claydite concrete. The calculation values are obtained according to the suggested method.

The calculations in Table 2 suggest that the method is in good agreement with the experimental data.

Table 2

Comparison of the experimental and theoretical values of the lower η^0_{crc} and upper η^v_{crc} limits of microcracking

Age of concrete, days	Prismatic density f_{lc}, MPa	Cubic strength $f_{lc,cube}$, MPa	Calculaiton density ρ, kg/m^3	Ratio $\eta^0_{crc}/\eta^v_{crc}$		Empirical coefficients		Microcracking limits				Deviation of the calculation values from the empirical ones, %	
								lower		upper			
				actual	accepted	k_{c1}	k_{crc}	$\eta^{0\,on}_{crc}$	$\eta^{0\,расч}_{crc}$	$\eta^{v\,on}_{crc}$	$\eta^{v\,расч}_{crc}$	$\Delta\eta^0_{crc}$	$\Delta\eta^v_{crc}$
Actual class of claydite concrete													
LC 8.4/10.3													
7	6.4	8.06		0.639	0.6	1.55	0.93	0.45	0.42	0.701	0.67	6.3	4.5
14	6.88	8.64	1050	0.596	0.6	1.55	0.93	0.42	0.44	0.711	0.69	−4.2	2.7
28	**8.36**	**10.30**		**0.674**	**0.6**	**1.55**	**0.93**	**0.52**	**0.50**	**0.769**	**0.75**	**3.1**	**2.3**
LC 9.9/11.8													
14	7.12	8.92		0.627	0.6	1.35	0.81	0.47	0.37	0.750	0.62	20.3	16.7
21	8.27	10.11	1450	0.632	0.6	1.35	0.81	0.48	0.41	0.759	0.66	13.6	12.4
28	**9.89**	**11.82**		**0.612**	**0.6**	**1.35**	**0.81**	**0.48**	**0.46**	**0.779**	**0.71**	**3.0**	**8.5**
60	11.17	13.61		0.650	0.6	1.35	0.81	0.51	0.50	0.791	0.75	3.7	5.8
LC 16.2/20.6													
7	13.11	16.04		0.628	0.6	1.35	0.81	0.54	0.54	0.857	0.79	0.0	8.1
14	14.68	18.10	1450	0.654	0.6	1.35	0.81	0.53	0.57	0.812	0.82	−7.0	−0.8
28	**16.21**	**20.56**		**0.651**	**0.6**	**1.35**	**0.81**	**0.51**	**0.59**	**0.776**	**0.84**	**−17.7**	**−8.8**
60	17.56	21.47		0.742	0.6	1.35	0.81	0.56	0.62	0.755	0.87	−10.0	−14.7

End of Table 2

Age of concrete, days	Prismatic density f_{lc}, MPa	Cubic strength $f_{lc, cube}$, MPa	Calculaiton density ρ, kg/m^3	Ratio η^0_{crc} / η^v_{crc}		Empirical coefficients		Microcracking limits				Deviation of the calculation values from the empirical ones, %	
								lower		upper			
				actual	accepted	k_{c1}	k_{crc}	$\eta^{0\ on}_{crc}$	$\eta^{0\ расч}_{crc}$	$\eta^{v\ on}_{crc}$	$\eta^{v\ расч}_{crc}$	$\Delta\eta^0_{crc}$	$\Delta\eta^v_{crc}$
LC 23.7/29.5													
14	19.34	26.67	1850	0.646	0.6	1.15	0.69	0.488	0.52	0.755	0.77	−7.5	−2.6
21	21.19	28.72		0.650	0.6	1.15	0.69	0.501	0.55	0.771	0.80	−8.8	−3.2
28	**23.67**	**29.53**		**0.654**	**0.6**	**1.15**	**0.69**	**0.515**	**0.57**	**0.788**	**0.82**	**−10.8**	**−4.1**
60	24.69	31.04		0.673	0.6	1.15	0.69	0.535	0.58	0.795	0.83	−8.4	−4.4
LC 29.0/33.6													
14	21.37	24.60	1850	0.741	0.6	1.15	0.69	0.65	0.55	0.874	0.80	15.6	8.8
21	27.24	30.86		0.746	0.6	1.15	0.69	0.63	0.60	0.849	0.85	4.8	−0.4
28	**28.99**	**33.63**		**0.714**	**0.6**	**1.15**	**0.69**	**0.65**	**0.62**	**0.903**	**0.87**	**4.4**	**4.0**
60	29.86	34.07		0.717	0.6	1.15	0.69	0.64	0.62	0.895	0.87	2.9	2.4
Previously conducted studies [20]													
LC 9.1/11.7													
28	9.1	11.7	1450	0.577	0.6	1.35	0.81	0.41	0.44	0.71	0.69	−7.4	2.8
LC 10.7/13.5													
28	10.7	13.5	1450	0.603	0.6	1.35	0.81	0.44	0.48	0.73	0.73	−9.9	−0.5
LC 11.2/14.2													
28	11.2	14.2	1450	0.603	0.6	1.35	0.81	0.44	0.50	0.73	0.75	−12.7	−2.2
LC 15.9/20.2													
28	15.9	20.2	1650	0.667	0.6	1.25	0.75	0.5	0.53	0.75	0.78	−6.9	−4.6
LC 17.7/22.7													
28	17.7	22.7	1650	0.600	0.6	1.25	0.75	0.45	0.56	0.75	0.81	−24.7	−8.2
Mean deviation $\sum\Delta\eta_{crc}/n$. %												−2.4	1.0
Mean deviation of the absolute value $\sum\lvert\Delta\eta_{crc}\rvert/n$. %												8.9	5.6

Conclusions

1. As a result of the study it was found that the density of claydite concrete has an effect on the limits of microcracking.

2. The dependencies for calculating the relative values of loads corresponding with the lower and upper limits of microcracking. The formulas (1), (2) can be applied for concrete of different compression classes as well as concrete of different types.

3. The effect of the density of claydite concrete on the limits of microcracking is allowed for by the empirical coefficient k_{c1}. The values of the coefficient are identified based on the calculated density of lightweight concrete accepted in accordance with the *Eurocode* 2.

References

1. Akhmedov A. I. *Vliyanie mikrorazrushenii betona na ekspluatatsionnye kachestva stroitel'nykh konstruktsii*. Avtoref. diss. kand. tekhn. nauk [The impact of concrete micro-destruction on the performance of building structures. Cand. eng. sci. diss.]. Moscow, 2006. 22 p.

2. Berg O. Ya. *Fizicheskie osnovy teorii prochnosti betona i zhelezobetona* [Physical foundations of the theory of strength of concrete and reinforced concrete]. Moscow, Gosstroiizdat Publ., 1962. 96 p.

3. Bobrov V. V. *Metody otsenki vliyaniya razlichnykh faktorov na protsess mikrorazrushenii betona pod nagruzkoi*. Avtoref. diss. kand. tekhn. nauk [Methods for assessing the impact of various factors on the process of micro-destruction of concrete under load. Cand. eng. sci. diss.]. Moscow, 2015. 26 p.

4. Bobrov V. V. Mikrorazrusheniya betona pri tsentral'nom szhatii [Micro-destruction of concrete under Central compression]. *Arkhitektura i stroitel'stvo Rossii*, 2009, no. 10, pp. 26—37.

5. Evrokod 2. Proektirovanie zhelezobetonnykh konstruktsii. Ch. 1-1. Obshchie pravila i pravila dlya zdanii: TKP EN 1992-1-1-2009: vved. 01.01.10 [Design of reinforced concrete structures. CH. 1-1. General rules and regulations for buildings: tap EN 1992-1-2009: introduced 01.01.10]. Minsk, Minstroiarkhitektury RB Publ., 2015. 206 p.

6. Zinchenko S. V. *Mitsnist' ta deformativnist' konstruktsii iz tsementno-zol'nogo keramzitobetonu*. Avtoref. diss. kand. tekhn. nauk [Strength and deformability of structures made of cement-ash expanded clay. Cand. eng. sci. diss.]. Odessa, 2010. 21 p.

7. Istomin A. D., Belikov N. A. Zavisimost' granits mikrotreshchinoobrazovaniya betona ot ego prochnosti i napryazhennogo sostoyaniya [Dependence of the boundaries of concrete microfracturing on its strength and stress state]. *Vestnik MGSU. Stroitel'stvo. Arkhitektura*, 2011, no. 2—1, pp. 159—162.

8. *Rekomendatsii po podboru sostavov, izgotovleniyu i primeneniyu modifitsirovannykh khimicheskimi i mineral'nymi dobavkami konstruktsionno-teploizolyatsionnogo i konstruktsionnogo keramzitobetonov* [Recommendations for the selection of compositions, manufacture and use of modified chemical and mineral additives of structural and thermal insulation and structural expanded clay]. Minsk, 2013, 38 p.

9. Semenyuk S. D., Moskal'kova Yu. G. *Prochnost' i deformativnost' izgibaemykh zhelezobetonnykh elementov, usilennykh narashchivaniem szhatoi zony, pri staticheskom i malotsiklovom nagruzheniyakh* [Strength and deformability of the bent reinforced concrete elements strengthened by building up of the compressed zone at static and low-cycle loadings]. Mogilev, Belorus. — Ros. un-t, 2017. 274 p.

10. Bodnarova L., Hela R., Hubertova M., Novakova I. Behaviour of Lightweight Expanded Clay Aggregate Concrete Exposed to High Temperatures. *Engineering and Technology International Journal of Civil and Environmental Engineering*, 2014, vol. 8, no. 12, pp. 1210—1213.

11. Boma M. B., Brocato M. A continuum model of micro-cracks in concrete. *Continuum Mechanics and Thermodynamics*, 2010, vol. 22, no. 2, pp. 137—161. doi: 10.1007/s00161-009-0130-4.

12. Byard B. E., Schindler Anton K. Cracking tendency of lightweight concrete. Submitted to The Expanded Shale, Clay, and Slate Institute. Research Report. Harbert Engineering Center Auburn University, 2010. 93 p.

13. Chandra S., Berntsson L. Lightweight aggregate concrete. Science, Technology, and Applications. New York, U. S. A., Noyes Publications; William Andrew Publishing, 2002. 407 p.

14. Clarke J. L. Structural Lightweight Aggregate Concrete. Glasgow, UK, Blackie Academic & Professional, 2005. 161 p.

15. Dehn F. Fracture mechanical behaviour of lightweight aggregate concrete. International Association of Fracture Mechanics for Concrete and Concrete Structures (IA-FraMCoS). Available at: http://framcos.org/FraMCoS-5/Dehn.Fracture.pdf

16. Gunasekaran Mr. M., Saranya G., Elamaran L., e. a. Development of Light Weight Concrete by using Autoclaved Aerated Concrete. IJIRST — International Journal for Innovative Research in Science & Technology, 2016, vol. 2, no. 11, pp. 518—522.

17. Wang X. F., Fang C., Kuang W. Q., e. a. Experimental study on early cracking sensitivity of lightweight aggregate concrete. Construction and Building Materials, 2017, vol. 136, pp. 173—183.

18. Fenyvesi O. Affect of lightweight aggregate to early age cracking in concrete. Periodica Polytechnica. Civil Engineering, 2011, no. 55/1, pp. 63—71. doi: 10.3311/pp.ci.2011-1.08.

19. Lim C. C., Gowripalan N., Sirivivatnanon V. Microcracking and chloride permeability of concrete under uniaxial compression. Cement and Concrete Composites, 2000, vol. 22, no. 5, pp. 353—360.

20. Moskalkova Yu. H. Behavior of claydite at the stage of microcrack formation. Наука та будівництво, 2017, no. 3 (13), pp. 40—43.

21. Tao Ji, Zhang Bin-bin, Chen Yong-bo, Zhuang Yi-zhou Evaluation method of cracking resistance of lightweight aggregate concrete. Journal of Central South University, 2014, vol. 21, no. 4, pp 1607—1615.

22. Tomičić I. Analysis of lightweight aggregate concrete beams. Građevinar, 2012, no. 64 (10), pp. 817—824.

23. Henkensiefken R., Castro J., Bentz D. e. a. Water absorption in internally cured mortar made with water-filled lightweight aggregate. Cement and Concrete Research, 2009, vol. 39, no. 10, pp. 883—892. doi: 10.1016/j.cemconres.2009.06.009.

24. Yang Z., Weiss W. J., Olek J. Interaction between Micro-Cracking, Cracking, and Reduced Durability of Concrete: Developing Methods for Considering Cumulative Damage in Life-Cycle Modeling. Indiana, Purdue University, 2005. 265 p.