საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 18, №2, 2024
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 18, no. 2, 2024

Materials Science

Time-Varying Moisture Content in Cement-Based Composite's Creep Issues during Tension

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The processes of material's moisture conductivity with the environment (drying, moistening) and their influence on the creep of cement-based composites are investigated. Long-term tension tests are conducted on specimens of concrete and steel-fiber concrete. During the creep test, the specimens (flat "eight" with 50 mm thickness, with total length of 530 mm and working part width of 70 mm) experienced a process of drying and moistening with different intensities. Experiments reveal that creep deformations intensify at tension during specimen drying and moistening processes. Therefore, using the accepted method of moisture permeability theory, a sample with a rectangular cross-section is considered a round stem with a radius chosen so that the area of specimen's cross section is unchanged. Equations according to time and radius to be usable in variable moisture cylindrical specimen tension tasks are created and based on the concrete tension-compresion creep nucleus universal expression established by us. By dividing the cross-section of a cylinder into circles of N quantity according to the radius, we derive Volterra's second-kind integral equation for each circle. The known variables in the equation are creep deformations (determined from experiments); tension-compresion creep nucleus and variable moisture values (determined by theoretical processing of experimental data). The stresses remain unknown, and the main task of the experiment is to define them. The stress values in each circle are determined by solving the equation with the numeric method. Stress determining method is established. *© 2024 Bull. Georg. Natl. Acad. Sci.*

composite, concrete, steel fiber concrete, tension, tension-compresion creep nucleus, moisture content, deformation

The dependence of concrete and steel fiber concrete creep deformations on moisture conductivity with the environment (drying, moistening) is determined. "Standard" specimens were tested as described in [1, 2]. Flat "eight" with 50 mm thickness, with total length of 530 mm and working part width of 70 mm for tension tests, age $t_0 = 28$, moisture content $W_0 = 4.7\%$, according to mass [1,2].

Short-term tests [1] determined that the concrete had a strength of 3.55 mpa while the steel fiber concrete was 48.24 mpa. The elasticity modulus for these materials was $E = 2.98 \cdot 10^4$ mpa and $E = 3.26 \cdot 10^4$ mpa, respectively [1,3]. Long-term creep tests are conducted on 12 special testing machines that are known and approved [1, 2].

During materials drying process in creep tests the specimens were tested in the environment with 100, 70, 50, and 20% relative humidity. In experiments during moistening process of materials, specimens were dried up to $W_0 = 1.0\%$ according to mass and tested in the environment of 20 and 100% relative humidity. The duration of all experiments was 240 days. Specimens in the tension tests were tested by "Standard" specimens rupture strength value of 0.5.

In parallel to creep tests, the equilibrium moisture content of materials (cylinders with diameters of 70 mm and lengths of 70 mm with isolated ribs) was determined using the weighing method in the intended relative humidity environment. During the drying process in the environment with 100, 70, 50, and 20% relative humidity, the equilibrium moisture content in both composites was identical and equaled W=4.7; 3.1; 2.0; and 1.0 % according to mass respectively. During moistening in 20 and 100% relative humidity environments, the equilibrium moisture content in specimens was 1.0 and 3.8% according to mass (see Table).

Table. The dependence of composite's creep deformations on the intensity of moisture conductivity with environment

Testing environment relative humidity φ, %	Specimen moisture content at the end of test W, %	Deformations $\varepsilon_{11} \cdot 10^{-6}$ In time, $t - t_0$, day $t - t_0$								
		0	2	5	10	30	60	120	180	240
1	2	3	4	5	6	7	8	9	10	11
Drying, concrete, beginning $W_0 = 4.7\%$										
100	4.7	59	80	90	110	115	130	138	140	142
70	3.1	68	84	100	117	144	160	174	185	191
50	2.0	61	94	104	120	160	184	195	200	203
20	1.0	60	94	104	128	170	202	214	219	221
Drying, steel fiber concrete, beginning $W_0 = 4.7\%$										
100	4.7	124	153	189	215	247	270	296	304	312
70	3.1	132	185	198	215	259	292	304	310	315
50	2.0	134	189	202	224	265	301	313	320	325
20	1.0	136	194	208	229	275	314	324	329	331
Moistening, concrete, beginning $W_0 = 1.0\%$										
20	1.0	57	60	64	68	74	77	82	83	84
100	3.8	60	102	120	139	176	209	220	224	226
Moistening, steel fiber concrete, beginning $W_0 = 1.0\%$										
20	1.0	130	144	157	167	170	175	181	183	185
100	3.8	132	195	212	234	281	322	335	341	345

The data from Table show that long-term deformations of both composites are increasing intensively in both (drying and moistening) cases. During the moisture conductivity with the environment, creep and relaxation processes that are complex and simultaneous take place in specimens. These processes are influenced by humidity gradient, during which the moisture content of material according to the specimen's lateral section is different over time and therefore, stresses according to the lateral section will vary. To solve material creep issues in terms of the free moisture conductivity process with the environment, it is necessary to know the regularity of moisture content change in specimens. This type of issue is solved for cylindrical specimens variable moisture content in given humidity terms is a function of (for a cylinder) R radius and t time. Solving problems of time-varying moisture contained materials creep issues (according to the conditions of our experiments when moisture exchange occurs from the specimen's entire lateral surface) in tensile testing specimens of cylindrical form is required. Therefore, using the accepted method of moisture permeability theory a sample of rectangular cross-section $F = 70 \times 50 = 350\,\text{mm}^2$ is considered as round stem which radius is selected so that the area of specimen's cross section is unchanged. In our case the radius of selected cylinder is R=33.4 mm.

Universal expression of the tension-compression creep nucleus was created for various t_0 age and W moisture content of concrete. After some modifications to be used in specimens tension tasks that have variable moisture content according to time and radius will be expressed as follows:

$$\Pi_p(t,\xi,W)=\left(\frac{t_{CT}}{\xi}\right)^{\alpha}\left[\pi_0\text{-}\pi_1(\upsilon\text{-}\upsilon_0)\times\ln\frac{t\text{-}\xi}{t_c^1}\right]. \tag{1}$$

In [1,2] and in equation (1), t is time counted from the specimen manufacturing moment $(t=0)$; ξ – any moment in interval $0 \le \xi \le t$; $\xi = t_0$ – the start of load (specimen age), in (1) $\Pi_p(t,\xi,w)$ nucleus is obtained from [1,2] by substitution of t_0 with ξ ; t_{CT} – "Standard" specimen age $t_{CT} = t_0 = 28$ day; α – quality indicator; for concrete $\alpha = 0.2$, for steel fiber concrete $\alpha = 0.15$ [1]:

$$\pi_0 = \gamma \cdot A\ ;\ \pi_1 = \frac{\gamma \cdot W_c}{\upsilon_0 \cdot W_m}\ ;\ t_c^1 = \frac{t_1}{t_c^{II}} \tag{2}$$

$$\upsilon = \frac{W - W_c}{W_0 - W_c}\ ;\ \upsilon_0 = \frac{W_c}{W_c - W_0}, \tag{3}$$

where W_0 denotes specimen moisture content at the beginning of test; W_C moisture content at the end of test; W moisture content during test; $0 \le W \le W_0$; W_m maximum moisture content 100% in relative humidity environment, in our case $W_m = 4.7\%$ according to mass; $t - \xi = t - t_0 \le t_1 = 2,\ t_1 = 2$ [1]. A, γ, t_c^{II} is determined from the ratios:

$$A=\frac{A_P(t_{CT},0)}{\gamma}\ ;\ \gamma = B_P(t_{CT},W_m)\cdot \lg e\ ;\ \lg t_c^{II} = \frac{A_P(t_{CT},W_m) - A_P(t_{CT},0)}{B_P(t_{CT},W_m)}. \tag{4}$$

$A_P(t_{CT},W_m)$; $A_P(t_{CT},0)$; $B_P(t_{CT},W_m)$ coefficient values are calculated from the data of Table with corresponding formulas [1,2].

From theory [4] υ is defined by the formula:

$$\upsilon(r,t) \equiv \upsilon(\rho,\tau) = \sum_{n=1}^{N} A_n \cdot I_o(\rho,\mu_n)\cdot e^{-\mu_n \cdot \tau}. \tag{5}$$

In (5) coefficient values and their defining methods are given in [4]. According to radius during the variable moisture cylinder tension P(t) strength is expressed by inner stresses with σ_{11} :

$$P(t) = 2\pi \cdot R^2 \int_0^1 \sigma_{11}(\rho,t)\cdot\rho\cdot d\rho, \tag{6}$$

where R radius of cylinder; $0 \le r \le R$; $\rho = \frac{r}{R}$; $0 \le \rho \le 1$.

For $\sigma_{11}(\rho,t)$ stresses integral equations are accepted that express there tension $\varepsilon_{11}(t)$ during the intended moisture content on the outer surface of cylinder $W(\rho,t)$ of infinite order according to - ρ and - t or moisture relative difference at body point on frontier (ρ,t). The integral equation is

$$\int_{t_0}^{t} \Pi_p\left[t,\xi,\upsilon(\rho,\xi)\right] d\sigma_{11}(\rho,\xi) = \Pi_p\left[t,t_0,\upsilon(\rho,t)\cdot\sigma_{11}(t)\right] - \int_{t_0}^{t} \cdot\sigma_{11}(\rho,\xi)\cdot d\Pi_p(t,\xi) = \varphi_{11}(\rho,t). \tag{7}$$

$$\varphi_{11} = \varepsilon_{11}(t) - \frac{1}{3}\Theta^* \cdot (t) = \varepsilon_{11}(t) - \frac{1}{3}\Theta_0^*\left[1 - \upsilon(p,t)\right],$$

$$\frac{1}{3}\Theta_0^* = \beta\left(W_C - W_0\right),$$

where Θ_0^* is the deformation of shrinkage or swelling; β – linear coefficient of shrinkage or swelling.

Here and hereafter, it means that tension deformations, (swelling deformations) are positive; (shrinkage deformations) are negative in creep tasks during tension:

$$t < t_0,\ P = 0;$$

$$t \ge t_0,\ P(\xi) = P_0 \cdot h(\xi - t_0),\ \xi > t_0,$$

wherein solving equation (7)

$$\sigma_{11}(t) = 0,\ t < t_0,$$

$$\sigma_{11}(t) \ne 0,\ t \ge t_0,$$

or otherwise:

$$\sigma_{11}(r,\xi) = F(\rho,\xi) \cdot h(\xi - t_0).$$

Therefore,

$$\varepsilon_{11}(t) = \varepsilon_{11}(t) \cdot h(t - t_0)$$

$$d\sigma_{11}(r,\xi) = \frac{\partial F(\rho,\xi)}{\partial \xi} \cdot h(\xi - t_0) \cdot d\xi + F(\rho,\xi) \cdot \delta(\xi - t_0) \cdot d\xi,$$

where h is Heaviside step function, δ is Dirac function $d\sigma_{11}(r,\xi)$, including expression in (7) formula is expressed as follows:

$$\int_0^t \Pi_p\left[t,\xi,\upsilon(\rho,\xi)\right] \cdot dF(\rho,\xi) = \varepsilon_{11}(t) - \varepsilon_{11}(t_0)\frac{\Pi_p(t,t_0)}{\Pi_p(t_0,t_0)} - \frac{1}{3}\Theta_0^*\left[1 - \upsilon(\rho,\xi)\right] \equiv \Delta\varepsilon_{11}, \tag{8}$$

$\Pi_p(t,t_0) = \Pi_p(t,t_0,\upsilon = 0)$ creep nucleus during infinite moisture $\upsilon = 0$

$\Pi_p(t_0,t_0) = \Pi_p(t_0,t_0,\upsilon = 0)$ creep nucleus during instant load and infinite moisture $\upsilon = 0$

Intended $P = P_0 \cdot h(t - t_0)$ during test (table data) will define $\varepsilon_{11}(t)$ and $\varepsilon_{11}(t_0)$.

Equation (8) is solved for continuous function $F(\rho,\xi)$, $t_0 \le \xi \le t$ in (8)

$$\frac{\Pi_p(t,t_0)}{\Pi_p(t_0,t_0)} = 1 + \frac{\pi_1}{\pi_0} \cdot \upsilon_0 \cdot \ln\frac{t - t_0}{t_c^1}.$$

Separating $\rho = 0; 0.1; \ldots \rho_i; \ldots 0.9; 1,\ (i = 1,2,3\ldots\ldots N)\ (0 \le P \le 1)$ from formula (8) for each – ρ_i we have Volterra's second kind integral equation:

$$\int_0^t \Pi_P\left[t,\xi,\upsilon(\rho_i,\xi)\right] dF_i(\xi) = \Delta\varepsilon_{11}, \tag{9}$$

where $F_i(\xi) = F(\rho_i,\xi)$, $(i = 1,2,3\ldots\ldots N)$.

In equation (9), $\Delta\varepsilon_{11}$ is known from the data in the Table, Π_P and υ are defined from (1), (5), [1,2,4], solving the tasks with respective formulas and thus, are known. In equation (9), stresses remain unknown $F_i(\xi)$. By solving the equation with numerical method $F_i(\xi)$, stresses for each i – circle are found, $F_1(\xi); F_2(\xi); \ldots . F_N(\xi)$. Subsequently, from equation (6) we get:

$$\tilde{P}(\xi) = 2\pi \cdot R^2 \sum_{i=1}^{N} F_i(\xi) \cdot \rho_{icp}(\rho_{i+1} - \rho_i), \quad (10)$$

$$\tilde{P}(t) = \tilde{P}(\xi)\big|\xi = t; \ \rho_{icp} = \frac{\rho_{i+1} + \rho_i}{2}.$$

Comparing $\tilde{P}(t)$ to - $P(t) = P_0 \cdot h(t - t_0)$

if $\left|\frac{\tilde{P}(t) - P_0}{P_0}\right| \ll 1$ the theory is reflecting creep well during the variable moisture.

მასალათმცოდნეობა

დროში ცვალებადი ტენიანობის ცემენტის ფუძიანი კომპოზიტების ცოცვადობის ამოცანა გაჭიმვისას

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(წარმოდგენილია აკადემიის წევრის რ. ხუროძის მიერ)

გამოკვლეულია ცემენტის ფუძიანი კომპოზიტების ცოცვადობაზე გარემოსთან ტენგაცვლის (გამოშრობა, დატენიანება) გავლენის საკითხები. ჩატარებულია ბეტონის და ფოლადფიბრობეტონის ნიმუშების ხანგრძლივი ტესტები გაჭიმვაზე. ექსპერიმენტში ცოცვადობაზე გამოცდის დროს ნიმუშები (ბრტყელი „რვიანი“ 50 მმ სისქის, საერთო სიგრძით 530 მმ და სიგანით მუშა ნაწილში 70 მმ) განიცდიდა გამოშრობასა და დატენიანებას სხვადასხვა ინტენსივობით. ექსპერიმენტმა გვიჩვენა რომ გაჭიმვისას ცოცვადობის დეფორმაციები ინტენსიურად იზრდება როგორც ნიმუშების გამოშრობის, ისე დატენიანების დროს. ტენგამტარობის თეორიაში მიღებული ხერხის გამოყენებით სწორკუთხა კვეთის ნიმუშებს განვიხილავთ როგორც მრგვალ ღეროებს, რომლის რადიუსი შერჩეულია ისე, რომ ნიმუშების განივი კვეთის ფართი არ იცვლება. ცვალებადი ტენიანობა მოცემულ ტენიან პირობებში არის ფუნქცია რადიუსის და დროის. ჩვენ მიერ შექმნილი ბეტონების კუმშვა-გაჭიმვის ცოცვადობის ბირთვების უნივერსალური გამოსახულების საფუძველზე შემუშავებულია განტოლება დროისა და რადიუსის მიხედვით ცვალებადი ტენიანობის ცილინდრული ნიმუშების გაჭიმვის ამოცანებში

გამოსაყენებლად. ცილინდრის განივკვეთის რადიუსის მიხედვით დაყოფით N რაოდენობის რგოლად გვაქვს თითოეული რგოლისთვის ვოლტერას მეორე რიგის ინტეგრალური განტოლება. განტოლებაში ცნობილია: ცოცვადობის დეფორმაციები ექსპერიმენტებიდან; კუმშვა-გაჭიმვის ცოცვადობის ბირთვების და ცვალებადი ტენიანობის განსაზღვრული სიდიდეები. უცნობი რჩება ძაბვები, რომელთა დადგენა გამოკვლევის ძირითადი ამოცანაა. თითოეულ რგოლში ძაბვების დადგენა ხდება განტოლების რიცხვითი ამოხსნის მეთოდით. შემუშავებულია ძაბვების განსაზღვრის მეთოდიკა.

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Received February, 2024