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FILLER ADHESION THEORY BY CEMENT STONE

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Abstract.

The article described the factors that increase the grip of a binder with a filler, thus they allow to improve the physical and mechanical properties of an artificial construction conglomerate. On the basis of Lame equation and experimental data the laws of shrinkage and deformation influence were formulated concerning a binder and the thickness of a cement-sand shell around the grains of a large filler on the crack resistance of a cement-sand concrete matrix. The maximum fracture toughness was shown by cement-sand mortar around the filler with the minimal shrinkage and the thickness corresponding to the ratio of shell thickness to the aggregate grain radius $\Delta r/r$ = 0,3-0,4. The introduction of 10-20% of fine mineral admixtures (quartz, granite screenings of crushing, limestone) reduces the shrinkage stresses of the concrete cement-sand component. Own shrinkage and expansion deformations can play both positive and negative role.

A proper design of an artificial construction conglomerate composition and the conditions of formation will provide a high strength, the improved deformation properties and corrosion resistance.

Keywords. Shrinkage deformations, fracture resistance, concrete, adhesion, filler, cement matrix.

Introduction.

The theory of concrete and reinforced concrete assumes the existence of physical adhesion forces between a cement matrix and a large filler, conditioned by the cement stone contraction due to its shrinkage, as well as by the local sites of chemical coupling and the donor-acceptor interaction between a cement matrix and a filler. A rather full implementation of adhesion and friction forces should have a sufficiently tight contact of a binder and a filler surface in concretes or in a general way, the tight contact of interphase surfaces of an artificial building conglomerate [1, 2].

As is known, the mark of a filler for heavy concretes is usually considerably higher by strength than a cement-sand matrix. The contact strength of a heavy concrete binder part to a large filler is weaker, so the contact zone is usually the weakest link of artificial building conglomerates [3, 4]. In this regard, the most important area of construction and technical properties improvement and the enhancement of longevity is the strengthening of a binder and a filler link.

Methods. The clutch was studied conditioned by the adhesion and the friction of a cement-sand ring with an outer and an inner surface of steel cylinders. For this purpose the gap between two cylinders was filled by the mortar with W/C = 0.4. At that an inner ring simulates a large filler of a circular shape, and an outer ring simulates the surface of the neighboring filler grain. Portland cement was used in the experiments without the additive CEM I 42,5 N. The samples were hardened within 24 hours at the temperature of 80 C within the environment of saturated water steam. After their drying and cooling to a room temperature, the cement stone adhesion forces were measured with an inner and an outer surface, extruding an inner and then an outer (or vice versa) cylinders separately by tangentially applied load.

Main part. Concrete science assumes that one of the reasons of close enough binder adhesion to a filler and a reinforcement is the presence of contraction forces due to shrinkages, but not all experts agree with the presence of such forces [5]. The provision of the cement-sand shell (a ring) optimum thickness plays an important role in order to increase the fracture resistance around this ring due to the tangential component of the own deformations and stresses during shrinkage. On the basis of Lame theory the equations were proposed for the calculation of radial and tangential deformations during shrinkage:

$$\sigma_r = \frac{-\Delta \mathcal{E}\left(1-\frac{a^3}{b^3}\right)}{\frac{1}{2E_2}\left[\left(2\frac{a^3}{b^3}+1\right)-\mu_2\left(4\frac{a^3}{b^3}-1\right)\right]+\frac{1}{E_1}\left(1-\frac{a^3}{b^3}\right)(1-2\mu_2)} \qquad (1)$$

$$\sigma_\tau = \frac{-\Delta \mathcal{E}\left(2\frac{a^3}{b^3}+1\right)}{\frac{1}{E_2}\left[\left(2\frac{a^3}{b^3}+1\right)-\mu_2\left(4\frac{a^3}{b^3}-1\right)\right]+\frac{2}{E_1}\left(1-\frac{a^3}{b^3}\right)(1-2\mu_1)} \qquad (2)$$

Where E_2 - the elasticity module of a cement stone; E_1 - filler elasticity module; μ_1 and μ_2 - Poisson's ratios of a cement stone and a filler respectively; a - the radius of a filler grain; b - the radius of a grain filler with a cement shell. The diagram (Fig. 1) shows the direction of the radial and tangential shrinkage deformations in the concrete made of ordinary cement which does not contain any expanding additives.

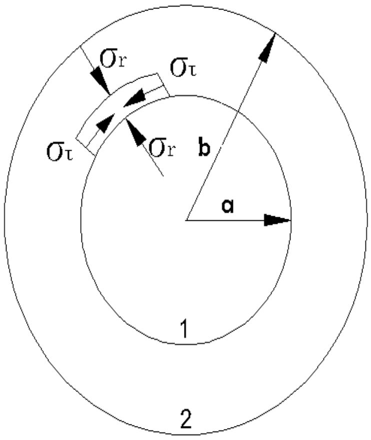

Fig. 1. The scheme of cement stone deformation during shrinkage:1 - filler; 2 - cement stone.

During the expansion in the equation (1) $\sigma_r < 0$, and in the equation (2) $\sigma_\tau > 0$. During the shrinkage of an ordinary cement when a tends to b, the thickness of the ring tends to 0 (Fig. 1), the tangential component becomes very large, which leads to the appearance of large tensile stresses in a stone, causing transverse cracks, which is confirmed by performed experimental studies. If on the contrary, a tends to 0 at b = const, then the filler adhesion to the concrete cement matrix is reduced.

Lame formula demonstrates that the tangential stresses in the cement ring of a normal shape are more than radial ones, so they are responsible for the appearance of contraction forces, causing quite a dense filler clamping by the inner surface of a cement shell.

These data provide the interest associated with the use of cements in aggressive environments which allows to make an important conclusion: in order to reduce the tangential stresses which cause the cracking of a shell and a contact area, it is necessary to reduce the shrinkage deformations of cement-sand concrete component. To do this, it is advisable to introduce some finely ground mineral supplements of quartz, granite, limestone crushing screenings, etc. This technique allows you to reduce the shrinkage stresses and improve corrosion resistance at the introduction of mineral supplements even in small quantities. It is better to use mineral additives with a positive electric surface charge, namely limestone, which greatly reduces shrinkage deformations for Portland cement. However, an excessive amount of mineral supplements is able to reduce the strength and increase the porosity of a concrete cement matrix [6, 7]. Thus, it is advisable to limit the quantity of additives by 10-20%.

The works [8-10] show the results of calculations concerning the own deformation of cement stone and concrete. At that they used the calculation of elastic deformations and continuous medium stresses proposed by Lame. The calculation results are consistent with the experimental data. The mentioned studies considered only tangential stresses and the radial ones were not considered. This greatly impoverished the effectiveness of research and did not allow to obtain practical important results.

Bond strength is determined by the amount of adhesion and surface friction. Adhesion strength can be determined by the separation of one material surface from another one by a normally applied load, and the influence of friction forces at the separation of surfaces from each other by tangential load.

On the basis of performed research they found out that the adhesion of a cement stone from the normal shrink Portland cement with an inner surface has always been more than with an outside surface, which is consistent with Lame formula. The adhesion of a cement stone with an inner surface increases with the increase of an inner ring radius up to a certain limit, and then, reaching a maximum value, it is decreased with the further increase of this ratio. This is conditioned by shrinkage deformations of the binder and the associated emergence of contraction forces. The diagrams are presented below showing the resulting action of shrinkage forces (Fig. 2).

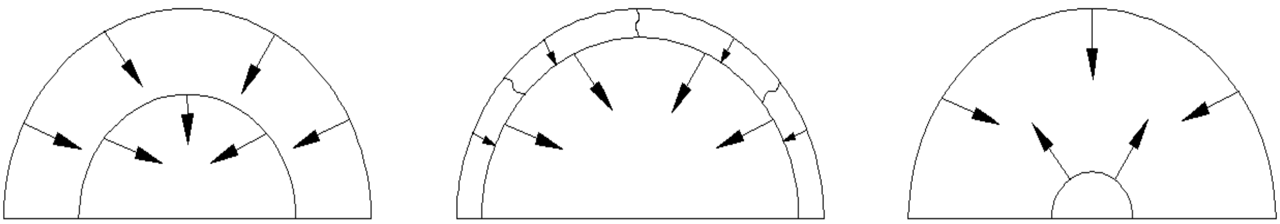

Fig. 2. Ring shape impact concerning own shrinkage deformations of a cement stone.

It is interesting that at a very large thickness of a cement ring and a small inner cylinder radius the cement ring was behind an inner surface, the increase of the inner ring radius or a "negative clutch" was observed. A cement ring clutch with an inner and an outer surface of the cylinders is equal to zero also at very small cement ring thickness, i.e., at a small ratio R:r. At that transverse cracks appeared on samples.

On a cement stone of an expanding compound the results determining the clutch were different one. It was found that the adhesion of expanding cements from an outer surface is greater than from an inner surface. In all experiments with the expanding cement the increase of a ring outer diameter was observed. As for the inner diameter, its behavior depended on a ring thickness. The inner radius increased at small thickness. If the inner radius was very small (about R:r = 5:1 ... 10:1), the inner surface compression was observed due to the reduction of an inner ring radius.

Thus, the shrinkage of a cement stone by magnitude and direction was strongly dependent on a ring shape, i.e. the ratio of the outer ($r_н$) and the inner radius ($r_в$).

The work [11] examined the effect of cement stone deformations on the values of a cement shell diameter around the grains of a large filler, which complicated somewhat the conclusion of work results. In this regard, we proposed a modified conclusion with the use of a cement ring radii.

The shrinkage and the own voltages conditioned by it has some vector values, the numerical value and the direction of which depends on the ratio of a sample height, an inner and an outer diameter of a ring. During the consideration of a plane problem the basic role was played by the latter figure.

The radial component of the elastic shrinkage is the following one:

$$\Delta L_{рад} = (r_н - r_в)\, \varepsilon_{рад} \quad (3)$$

The tangential component of the elastic shrinkage along the inner and outer surfaces of a cement ring makes accordingly:

$$\Delta L_{тан\ в} = 2\pi r_в \cdot \varepsilon_{тан} \text{ и } \Delta L_{тан\ н} = 2\pi r_н \cdot \varepsilon_{тан}, \quad (4)$$

Where $\varepsilon_{рад}$ and $\varepsilon_{тан}$ is the specific shrinkage per unit of a cement ring thickness or per unit of a cement ring length, $r_н$ and $r_в$ – an outer and an internal radius of a cement ring.

Obviously, the specific shrinkage is somewhat greater by length than by thickness, but in order to simplify the task let's take $\varepsilon_{рад} \approx \varepsilon_{тан}$.

Let’s consider:

$$\Delta L_{тан\ в} / \Delta L_{рад} = 2\pi r_в \cdot \varepsilon_{тан} / (r_н - r_в)\, \varepsilon_{рад} \quad \text{and} \quad (5)$$

$$\Delta L_{тан\ н} / \Delta L_{рад} = 2\pi r_н \cdot \varepsilon_{тан} / (r_н - r_в)\, \varepsilon_{рад}, \quad (6)$$

Where $\Delta L_{тан\ в}$ is the tangential shrinkage along the inner surface of the cement ring, $\Delta L_{тан\ н}$ is the tangential shrinkage along the outer surface of a cement ring.

Hence:

$$\Delta L_{тан\ в} / \Delta L_{рад} = 2\pi r_в / (r_н - r_в) \quad (7)$$

$$\Delta L_{тан\ н} / \Delta L_{рад} = 2\pi r_н / (r_н - r_в) \quad (8)$$

Obviously $2\pi r_н$ is always larger, than ($r_н$-$r_в$), thus a cement ring during shrinkage will always be behind an outer surface which contacts it.

During the increase of a cement ring inner radius, i.e. the relations $2\pi r_н/(r_н - r_в)$ in excess of the allowable limit the tangential component of the own stresses increases so that there is a rupture of its continuity, i.e., the appearance of major transverse cracks visible to a naked eye. The smaller the thickness of a ring at a constant outer diameter, the more shrinkage cracks it has. This leads to the fact that too much reduction of a cement shell thickness around a reinforcement a filler grains reduces the adhesion between them. Obviously, the lower the humidity of the environment, the greater this factor influences the physical and mechanical properties and the crack resistance of concretes. If the thickness of a cement ring is approximately equal to its length along the internal surface at a sufficiently small value of $r_в$, then:

$2\pi r_в = (r_н - r_в)$, т.е. $r_н = 7{,}28\ r_в$. Thus, at $r_н \approx 7{,}28\ r_в$ the cement ring does not create any pressure on the ring body, and at $r_н > 7{,}28\ r_в$ it is behind it, i.e. a «negative compression» of a filler is observed, and this was described at first in [1].

In A.I. Bulatov's and A.L. Vidovsky's [5] works the ratio of own stress sensor diameter of a cement ring to the outer diameter of the sample was close to a specified value. These authors questioned the possibility of filler and reinforcement grain compression by a cement stone. In [1, 12-14] these results are refuted completely.

The calculation shows that the lower $r_н - r_в$, i.e. the thickness of a cement ring, the greater the force of contraction. However, at too small thickness of a cement ring the tangential forces of contraction become too large and can cause a cement stone cracking.

The smallest deformations and the balance of radial and tangential deformations and stresses of the cement matrix with an immersed round-shaped body in it is observed at $(r_н - r_в)/r_в = 0{,}3–0{,}4$.

The above stated theoretical considerations have a qualitative agreement with the experimental data that the maximum strength of concretes is observed at the optimum thickness of a binder around the grains of a large filler, equal to (R-r) / r = 0,2-0,25 [3]. Shrink deformations, increasing the binder adhesion to one particle of a filler can cause the weakening of a bond with the other, a neighboring one, or cause the appearance of cracks in a binder. In this regard, the best option is a binder without shrinking. The factors influencing the adhesion of a binder with a filler are considered in the works [15-18]. In practice, the actual concretes have the maximum number of cracks in the areas with the greatest ratio of length to thickness. In the concrete with a rounded shape filler, depending on the manner of packing concerning the latter, develop the cavities made of a cement matrix at their junctions with a triangular or a rectangular shape and sharp edges. The latter will have the emergence and the development of shrink micro- and macro-cracks as their own tensile deformations and stresses will be higher than in interlayers between some filler individual grains. The reduction of concrete permeability for corrosive components can be controlled by the conductivity reduction of the contact surfaces not only by the rational choice of a binder and a filler type, and an optimal grain size of a large filler. The monograph by I. Shtark [19] showed that the increase of a large filler grain size from 8 to 16 mm increases the concrete permeability by 2.1 times and about three times at grain size increase from 8 to 32 mm. The mechanism established by Stark may be explained from the position of Lame theory: at the increase of a filler grain radius the tangential component of shrinkage stresses grows resulting in crack formation. Therefore, the larger a filler is, the greater should be the thickness of a cement-sand ring around filler particles, which reduces the tangential component of own shrinkage stresses. The confirmation of the above stated considerations are the data presented in the monograph [19]. These data show that the use of a fine filler in concretes reduces the permeability and increases the corrosion resistance of articles and structures, as compared to a large filler.

Conclusions. One of the reasons concerning concrete strength fall at the reduction of concrete mortar component consumption and, consequently, the thickness of a cement-sand shell (a ring) around the particles of a large filler is the ring fracture toughness reduction due to the tangential component excessive growth of its own strain and stress during shrinkage. In this regard, the concretes, hardening in air, especially in a low relative humidity should observe the maximum ratio P:C. The reduction of these parameters makes a minimal negative impact on physical and mechanical properties during the hardening in water as compared to air-wet hardening.

The greater the shrinkage of cement, the more negative effect on its resistance is made by the reduction of a cement shell thickness, therefore it is necessary to increase the shell thickness. Shells may be smaller in low shrink cement.

The place of the maximum concentration of own stresses in the heavy concrete structure, hardening in air conditions, are the rough edges on filler grains, as well as the joints between the particles of the latter. At the thickest cubic packing of large filler grains this structural element has a rectangular shape on a plane, and at hexagonal one it has a triangular shape. Cement-sand mortar in the second case has less resistance to cracks apparently.

In order to reduce the crack formation of a cement-sand element in the joints of a filler particles it is advisable to apply a second, smaller fraction, providing its dense packing, taking into account the availability of a cement-sand shell on them. As follows from [20], the ratio of this fraction diameter to a larger one should be ≈ 1:7.

When you use a large filler of continuous granulometry in heavy concretes the maximum amount is formed in the places where the tangential components of shrinkage stresses have the largest numeric value, i.e. around the largest grains of a filler, but also in the places where the thickness of a binder shell around the filler particles is the minimal one. The laws relating to heavy concretes with a large filler, and to the concretes with a fixed large filler are valid, apparently, in relation to the fine-grained concretes.

Summary. The above stated shows that the natural shrinkage and expansion deformation can play both positive and negative role. With a proper design of a composition and the conditions of an artificial construction conglomerate development they can acquire an exceptionally high strength, unique deformation properties and a corrosion resistance.

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