Physicochemical characteristics of bond and friction between the modified concrete and sliding formwork for the construction of high-rise buildings

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Summery. The article presents the research results of the interaction between formwork and freshly-mixed concrete. It is established that there is a significant bond and friction between the concrete and the sliding formwork at the moment of its rise.
Key words: concrete, formwork, bond.

INTRODUCTION

The development of modern housing construction, considering sharp price rise and shortage of land parcels in large cities, is directed toward the construction of high-rise buildings. This practice is widely known in the urban construction of civilized countries. Economics of high-rise residential buildings has a number of important advantages in comparison with the usual buildings. There is practically no alternative to such development of housing construction in large cities [Holland T.C. 1998, Zollo R. F. 1997]. However, the development of high-rise construction requires a special approach to the choice of basic material, creating the framework and the most important construction elements of buildings [Aкгoid T.M.B. 1980, Czernin W. 1998, Derucher K. M. 1989].

It is doubtless that heavy-weight concrete is this construction material [Hughes B. P., Gregory R. 1982, Reading T. J. 1987]. The uniqueness of the constructed residential buildings determines a complex of high operational requirements for this material [Vladimir Punagin 2010; Natalya Rudenko 2010]. First of all, they include high strength, resistance of heavy-weight concrete in various operating conditions, low radioactive background and the most possible durability at a relatively high economy of the selected material.

RESEARCH OBJECT

The existence of a significant bond and friction between the concrete and the sliding formwork at the moment of its rise was established experimentally. Negative consequences caused by the high friction and bond are also well-known. However, the nature of these phenomena has not been carefully studied yet and, in our opinion, the reason of it is the complexity of physicochemical phenomena and processes observed in the zone of contact of concrete with the formwork [Morinaga S. 1973, Schiller K. K. 1991, Willis J. R. 1982].

Concrete and sliding formwork, by analogy with the classical glue compounds, can be figuratively represented as the contact pair, where concrete acts as a glue (adhesive) and the formwork as a solid (the substratum). Their bond should be regarded as a result of mechanical anchor, adhesion, cohesion and shrinkage. The first three factors increase the bond and shrinkage reduces it.

The mathematical model of the bond in the general view is as follows:

$$\sigma_n = f(a) + f(k) + f(m) + f(y) + f(ak) + \\ + f(am) + +f(km) \pm f(ay) \pm f(ky) \pm f(my), \qquad (1)$$

where: σ_n – normal bond (tear force is perpendicularly to the plane of contact);

a – adhesion;

k – cohesion;

m – mechanical anchor (mechanical constituent);

y – shrinkage.

The impact of shrinkage on the bond can be fixed on technological and physical-mechanical level. Its value depends on the technological factors (mixture workability, terms of hardening), as well as the mineralogical composition of the cement matrix of concrete [Hanehara S., Yamada K. 2008, Sawaide M., Iketani J. 1992].

Mechanical anchor of concrete is determined by the surface roughness and porosity of the formwork and reveals mainly at the technological level.

RESULTS OF EXPERIMENTAL RESEARCH

It is established that various rough surfaces are moistened in different ways. The presence of unevenness (roughness) on hydrophilic surfaces leads to the reduction of the contact angle of Θ and, consequently, to the improvement of moistening rough hydrophilic surfaces in comparison with the smooth ones. On the contrary, roughness of hydrophilic surfaces increases the contact angle and worsens moistening. For this reason, the increase of roughness of hydrophilic formwork materials, such as steel, causes growth of bond of concrete. To reduce the negative consequences of this phenomenon we should strive to use steel formwork with pre-treated surfaces (grinding, polishing).

In our opinion, the assessment of formwork material should take into account not only its nature and roughness , but also the area of roughness. In particular, the increase of the distance between $x_o > x_{кр}$ and certain technological parameters of concreting lead to possible wetting and adhesion of concrete all over the unevenness surface or of the most part of it. Then due to sharp increase of the actual contact area the bond abruptly grows.

Roughness configuration, i.e., the shape and size of protrusions and cavities, also plays an important role for mechanical anchor. If large, but smooth asperities increase the bond only due to the increase in the actual contact area, the hook-shaped ledges and hollows when $x_o > x_{кр}$ simultaneously play the role of micro-anchors with the effect of microlacing contacting surfaces, that increases bond.

Technological factors (mixture workability, modes of compaction) also have a certain influence on mechanical anchor, as well as adhesion and bonding in whole. In the process of intensive compaction of the modified concrete in its zone of contact with the formwork, on the one hand, sharply decreases the viscosity of the mixture as adhesive, on the other hand – there is a heightened pressure in its joint layers. This increases the probability of penetration of the adhesive in the pores of the formwork and leads to a qualitative filling of surface asperities of the formwork, increasing the area of actual contact and, as a result, the bond. For a contact pair concrete - formwork the probability of mechanical anchor is great.

However, its importance should not be overestimated. Practical implementation of this component is only available in combination with other factors, such as adhesion. In our opinion, the mechanical anchor cannot be considered as a «dry lacing» of contacting bodies. Physical-chemical interaction of adhesive microvolumes with microareas of substratum surface asperities, i.e. in the points of microcontacts mechanical component is manifested through the adhesion.

The contact angle of moistening Θ may serve for the indirect characteristics of adhesion. It is established that the higher the moistening, i.e., the more cos Θ, the higher the adhesion, and vice versa.

The bond value of modified concrete with the formwork to a large extent depends on the cohesion of the adhesive, i.e. cement system. Cohesion depends on the degree of modification of the cement, the mineralogical composition, terms of setting and conditions of hardening.

It is established experimentally that the higher the strength of concrete, the greater the bonding between the concrete and formwork. Thus, the nature of the dependence of bonding on concrete strength other conditions being equal is determined by cohesion.

Adhesion and cohesion are two interrelated aspects of a process of a seam-contact formation. The kinetics of their growth over time reflects the processes of formation of structure of the adhesive (cohesion), and intermolecular interactions of contacting surfaces. At later terms, on the contrary, cohesion prevails over the adhesion. Here, apparently, there is an impact of shrinkage, which is less in a volume than in the contact zone.

In practice there are three cases of formwork separation (shift) depending on adhesion and cohesion ratio. The first one – plane separation (shift) coincides with the plane of the contact, adhesion is less than cohesion ($a<k$). This

separation (shift) is called adhesion. In this case the surface of the formwork is clean, the surface of the concrete is smooth. The second one - plane separation (shift) is held in the volume of concrete. In this case, the adhesion is much more than cohesion ($a>k$); separation (shift) is cohesive. In this case the surface is covered with cement crust, and the concrete becomes too rough. The third one - plane of separation partially coincides with the plane of contact, partially is held in the volume of concrete. It takes place at $a \approx k$. This separation (shift) is mixed. In this case there is partial increase of the cement crust on the formwork surface, and the surface of the concrete has a small not entire roughness. This type of separation (shift) in practice is observed most frequently.

Obviously, adhesion is the most important component of bonding concrete to the formwork.

In accordance with the adsorption theory of adhesion [Guzeyev E. A., Piradov K. A. 1998], adhesion is considered to be a surface phenomenon and is determined by the interaction Van-der-Waltz forces between the molecules of contacting objects. Manifestation of intermolecular forces is possible at approaching the contact surfaces on the distance of $5 \cdot 10^{-10}$ м. The main conditions of adsorption interaction are the maximum possible convergence of the contacting objects, the formation of the highest continuity of contact; the best moistening of the substratum surface with adhesive; the value of polarity of contacting objects.

The process of formation of contact between the concrete and formwork can be relatively divided into three stages.

On the first stage, as a result of intense compaction of the concrete mix there is an increasing convergence of contacting surfaces (concrete and formwork) at a distance of $5 \ldots 10 \cdot 10^{-10}$ м. It is quite possible, as the pressure rises in the contact zone, contributing to the destruction of the films on the surface of formwork (in particular, the film lubrication destroys) and removing of adsorbed bubbles of air on it. On the other hand, the viscosity of adhesive (cement system) is sharply reduced with vibration, this also contributes to the maximum convergence of the contacting surfaces.

The second factor is the continuity of contact. Considering the peculiarities of the contacting surfaces and conditions of technology, it can be asserted that the contact of modified concrete with the formwork has a pointed character.

The second stage is conventionally installed from the moment of termination of the mechanical impact (vibration) till the beginning of intensive structure formation.

Polarity of the contacting objects plays an important role in the implementation of intermolecular interaction at this stage, apart from the proper convergence. It is established that convergence of two polar or non-polar objects their intermolecular interaction is more, than of the objects, one of which is polar, and the other is non-polar.

It is difficult to establish the effect of polarity for the real conditions of a pair concrete - formwork, as long as the adhesive (concrete) is a multi-component conglomerate, and the surface of the framework is covered with various films. Despite this, during the construction of formwork for the deck such material should be chosen, which polarity would not correspond to the polarity of the adhesive.

The third stage of the adhesion seam is characterized by intensive structure formation. It is established, that this stage has two phases. Coagulation structure is formed on the first of them, and first hearths of crystallization structure appear. It is proved, that at the beginning the formation of hearths is more intensive on a solid surface, i.e. the formwork, than in the volume of concrete. As a result by the moment of shift adhesion becomes more cohesive, that leads to rapid accretion of shields with cement crust.

At the second stage in the zone of contact it is hardened neoplasms at the expense of transition coagulation-crystallization structure into crystallization-coagulation. At the same time with this hardening in joint layers of adhesive materials arise shrinkage tension, reducing adhesion.

The essence of the developed by S.S. Voyutskiy [Voyutskiy S. S. 1975] diffusion theory of adhesion consists in the following. When approaching the adhesive and the substratum at a distance, close to the size of the molecules, as a result of Brownian motion in the surface layers of contacting objects is the interpenetration of molecules (groups of molecules), i.e., their diffusion. The result is a durable contact seam between two dissimilar objects.

Manifestation of the diffusion components of such a type in the contact zone of concrete with the formwork is unlikely because of the hardness of the substrate and the small energy potential of the adhesive.

The process of adhesive microparticles penetration in the pores of the formwork, which is observed during the vibration compaction of concrete mixture, can be conditionally called macro-diffusion. The result is an increase in the mechanical anchor [Singh B. G. 1998, Sontige C. D., Hilsdorf H. 1993].

It is obvious that macro-diffusion appeares not only at the moment of vibration compaction, and will not end with its termination. In the period setting of this process continues as a result of penetration of microparticles growths in the pores and unevenness of formwork, especially this process intensifies when laying of the modified concrete mixture.

Macro-diffusive process in the zone of contact of concrete with the formwork is one-sided, i.e. it is accomplished on the side of the adhesive as a more mobile component.

Developed by B.V. Deryagin [Deryagin B. V., Krotova N. A. 1979] electrical theory of adhesion explains the interaction of two contacting bodies as a result of the formation of the double electric layer on the surface.

In real conditions the electric double layer can be of ordered or mosaic structure. According to the Deryagin's data, the risk of double electrical layer is higher in contact dielectric with the conductor and with intense friction of contacting surfaces.

In the zone of contact of concrete with metal formwork the appearance of a double electric layer, it is quite probable, as contact material (concrete) with metal at the intense friction (vibration compaction).

In the liquid phase of the modified concrete as adhesive materials at all stages of the formation of the contact (compaction, setting, hardening) contains the hydroxyl group HE is; in addition, in the zone of contact are ions of Ca^{2+}, Al^{3+}, $Al(OH)_4^-$, SiO_4^{4-}, O^{2-}. The surface of the steel, not having the products of corrosion, is characterized by the presence of hydroxyl groups OH^-, free electrons and ions Fe^{2+}. As a result of ion bond becomes complicated: the positive ions Fe^{2+} are donors for hydroxyl groups of the liquid phase of concrete, while the ions Ca^{2+}, Al^{3+} have arisen as a result of the transfer of electrons hydroxyl groups, which are on the surface of the steel. The result is a double electric layer of mosaic structures, various parts of which have different charges.

Therefore, the objective prerequisites for the emergence of in the zone of contact of concrete with the formwork of electric components of adhesion can be considered theoretically possible.

The absence of outer signs of electrization in violation of contact, i.e. when the formwork is shifted, in our opinion, is explained by the following: steel formwork has a very low ohmic resistance, as a result of the possibility of the formation in the zone of contact of surface electric charge is insignificant; the rate of rise of formwork so small that the electrons have time to flow down from the separated surfaces; presence of moisture in the contact zone does not contribute to the formation of surface charges. Therefore, for the moving formwork probability of electrical components is practically equal to zero. For other cases, for example, at immediate separation of plastic formwork and concrete products, hardened when drying infrared rays, it is much higher.

On Deryagin's opinion, every interaction at the molecular level (adsorption, electric) should be considered as a chemical bond.

The liquid phase of concrete as the adhesive is a strong alkaline environment, so the appearance of new formations in the zone of contact as a result of chemical interaction of concrete with the material of the deck is quite possible.

It is established by research [Anpilov S. M. 2005; Chernyavsky V. L. 1983] that the chemical interaction of cement stone can be also observed in metal with the formation of so-called intermetallic layer.

The result of chemical interaction of concrete and polymeric protective films can be explained by a relatively rapid destruction of such films on formwork panels and forms.

The force of friction $F_{тр}$ and normal pressure $P_н$ relation at «dry» friction can be expressed as follows:

$$F_{тр} = \varphi \cdot P_н , \quad (2)$$

where: φ – coefficient of friction.

When lifting, moving of formwork in the contact zone is the place of the complex interaction between the contacting surfaces, including, along with the «dry» friction adhesive interaction, i.e. the bond. This is just a generalized Deryagin's law, and the dependence takes the form

$$F_{тр} = \varphi\left(P_н + F_o\right), \quad F_o = \sigma_n \cdot S, \quad (3)$$

where: F_o – the strength of adhesion interaction of contacting surfaces, H;

σ_n – normal adhesion, MPa;

S – he contact area of the concrete formwork, $м^2$.

Adhesive component is observed not only at the moment of sliding formwork shift, but also in the process of its calm rise. In this case, apparently, the forces of the so-called non-contact adhesion take place. It becomes apparent on the surface areas, not adjoined directly, but located at intermolecular attraction radius distance from each other.

Thus, the generalized Deryagin's law of friction applies to practically all aspects of interaction of concrete with sliding formwork and in the best way reflects the regularities of interaction between those contacting surfaces.

There are real preconditions for the display of adsorptive, diffusive, electrical and chemical processes in real conditions of a contact pair concrete - formwork. Nevertheless, the technological conditions of contacting of concrete and formwork are so diverse (existence of various films on formwork, the degree of its roughness and porosity, different modes of vibration compaction, the characteristics of cements, mix rheology), and the mutual influences of different physical-chemical processes and phenomena in the contact zone are so complex that it is practically impossible to give a definite answer about the initial cause of adhesion.

Apparently, many factors and physical-chemical phenomena interconnected with each other are responsible for the adhesion, and, consequently, for the bond of concrete to the formwork. Therefore, the adhesion of concrete to the formwork should be considered as a multiple-factor phenomenon. Its mathematical model can be presented as following

$$a = f(A) + f(D_M) + f(E) + f(Ch), \qquad (4)$$

where: A – adsorption component;

D_M – the same, macro-diffusive;

E – the same, macro-diffusive;

Ch – the same, chemical.

The solution of the question about the nature and value of adhesion (bond) is possible at profound analysis of physical-chemical processes and surface phenomena occurring in the contact zone of concrete with the formwork. The complex of these processes and phenomena correlating with the identification of prevalent factors in this case should be taken into account to develop technological recommendations aiming reduction of bond and friction between the concrete and formwork.

CONCLUSIONS

1. It is established, that in monolithic constructions formation many factors and physical-chemical phenomena interconnected with each other are responsible for the adhesion, and, consequently, for the bond of concrete to the formwork. Therefore, the adhesion of concrete to the formwork should be considered as a multiple-factor phenomenon.

2. It is established that various rough surfaces are moistened in different ways. The presence of unevenness (roughness) on hydrophilic surfaces leads to the reduction of the contact angle of Θ and, consequently, to the improvement of moistening rough hydrophilic surfaces in comparison with the smooth ones. On the contrary, roughness of hydrophilic surfaces increases the contact angle and worsens moistening. For this reason, the increase of roughness of hydrophilic formwork materials, such as steel, causes growth of bond of concrete. To reduce the negative consequences of this phenomenon we should strive to use steel formwork with pre-treated surfaces.

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ФИЗИКО-ХИМИЧЕСКИЕ ОСОБЕННОСТИ СЦЕПЛЕНИЯ И ТРЕНИЯ МЕЖДУ МОДИФИЦИРОВАННЫМ БЕТОНОМ И СКОЛЬЗЯЩЕЙ ОПАЛУБКОЙ ПРИ ВОЗВЕДЕНИИ ВЫСОТНЫХ ЗДАНИЙ

Владимир Пунагин

Аннотация. В статье представлены результаты исследований взаимодействия опалубки и свежеуложенного бетона. Установлено наличие значительного сцепления и трения между бетоном и скользящей опалубкой в момент ее подъема.

Ключевые слова: бетон, опалубка, сцепление.