Abrasive wear of Cemented Granular Composites: Experiments and Numerical Simulations

N V Makarova¹², M V Polonik¹², A A Mantsybora¹

¹Institute of Automation and Control Processes of Far Eastern Branch of RAS, Radio str. 5, 690041 Vladivostok, Russian Federation
²Far Eastern Federal University, Sukhanova str. 8, 690950 Vladivostok, Russian Federation

E-mail: maknat@bk.ru

Abstract. The results of earlier experimental work and numerical calculations to determine the effects of technological parameters on abrasion resistance of concrete are summarized and new data presented. The dependences of the near-surface stress-strain state on the geometric and stiffness parameters are analyzed. Particular attention paid to the stages preceding the destruction of the adhesion interaction between cement matrix and grains. Numerical calculations were carried out in the ANSYS software. This numerical model may be useful for understanding heterogeneous material behavior in terms of wear, depending on structure geometrical characteristics, material mechanical properties and interactions occurring in the near surface layer. Adhesive laws gives very interesting advantages, of which the most important is to model the evolution of damage throughout the life of the building constructions.

1. Introduction

Abrasion erosion damage of concrete surface results from the abrasive effects of sand, gravel, rocks, ice, and other debris impinging on a hydraulic structure and continued movement of wheels on transport pavements during operation. The rate of erosion is dependent on a number of factors including the size, shape, quantity, and hardness of particles being, and the quality of the concrete. While high-quality concrete is capable of resisting high loading for many years with little or no damage, the concrete cannot withstand the abrasive action of debris grinding or repeatedly affecting its surface. In such cases, abrasion erosion ranging in depth from a few centimeters to meter or more can result depending on the operation conditions. These features of abrasion and deterioration processes and fracture should be considered when forecasting life cycle of concrete constructions.

Compared to the structures of metal, ceramics and other materials, to assess the strength and durability of the concrete structures the application of theoretical and experimental methods of the contact mechanics is difficult due to the significant heterogeneity of the concrete. Therefore, for a long time the study of the concrete abrasion resistance investigated mainly on experimental base [1-7]. The abrasion wear was predicted by used different empirical and statistical modelling depending on the amount and quality of data [8-9]

Models of concrete abrasion with consideration of its heterogeneous structure are presented in [10] and developed in [13]. In these papers, the surface abrasion is presented as a result of turning and falling out aggregate grains out of cement-sand matrix. The loss of grains occurs when the exposing of
grains reached a certain size comparable to the size of the coarse aggregate. At the same time for a sufficiently long operational period of structures, the surface abrasion takes place only due to wear of thin surface layers. In this regard, it is quite difficult to select criteria for the application of mathematical models of concrete surface abrasion at different structural levels.

In this work, based on the obtained experimental data and numerical calculations we study strength properties of concrete as composite material in the process of its abrasion. Particular attention is paid to the stages preceding the deterioration of the material. Numerical calculations were carried out based on the ANSYS software simulation model.

2. Statement of the problem

Abrasion process according to [11, 14-16] can be divided into the following stages:

Stage I - the initial stage, in which occurs the process of deterioration of the cement stone, solvation shells and exposing of the grains of coarse and fine aggregate;

Stage II - normal operating stage, in which takes place the process of abrasion of the grains of coarse aggregate and cement-sand matrix, and besides at different speed, depending on their physical properties. After the exposure of the surface of the coarse aggregate, the abraded surface presented by a set of areas with different tribological characteristics;

Stage III - the destruction of the concrete surface. There are two possible cases: case 1 - fatigue failure of the matrix occurs (extensive micro-cracking) between the grains of coarse aggregate, which leads to its loss, which is typical for concrete with low-strength cement-sandy matrix; case 2 - propagation of fatigue macro-crack on the border between the grains of coarse aggregate and cement-sandy matrix, which is typical of high-strength concrete (Figure 1).

![Figure 1. Failure mechanism associated with exposed aggregates (Stage III).](image)

In the paper [12] the choice of structural levels was based on experimental investigations. In order to application of mathematical models we carried out a series of experiments using a standard method (GOST 13087). In addition, 0.5-mm-long resistance strain gauge signals near abraded surface were registered by ADC-DAC module ZET210. As a result, it was found that in a certain, sufficiently long period of time, horizontal strain negligible and are stable (stage I and stage II). After that amplitude of strains occurred an abrupt increase (transition to the stage III). The greatest horizontal strains were observed at the height 0.7-1.5 of the maximum size of coarse aggregate, rather than in the immediate vicinity of the abraded edge. This is explained by the work of the friction forces. By the help of sensors there was recorded a strain maximum on the border between aggregates and matrix, that is explained by the concentration of stresses around the solid inclusions. In [11-12] the development of fatigue cracks also been tested. The experimental results showed that the cause for cracks propagation on the contact is the achieving by the relative deformations the limit values for concrete.

This experimental studies have shown that the process of abrasion of the concrete surface at the initial stages (stage I, II) occurs in sufficiently thin (<1 mm) layer and does not change the structure of the material in the near-surface zone. The rate of abrasion depends on the tribological characteristics of the concrete surface. In the future, it allowed to application more reasonably the mathematical apparatus of the mechanics of contact interaction.
3. Mathematical modelling

On the basis of the obtained experimental data mathematical modeling of abrasion in the initial stage I leads to modeling of concrete abrasion as a homogenous material [11-12]. The degree of abrasion is defined by \( \frac{\partial w^*}{\partial t} \) and depends on the speed \( v \), pressure \( p \) on the surface contact, material hardness \( H \), as well as the parameters that have a specific value for each abrasion process and used for its modeling.

Mathematical modeling in stage II comes to modeling of abrasion of material with an inhomogeneous structure. The softer cement matrix is failure, as result a coarse aggregate grains are exposed on the surface. In this study the application of mathematical models used for stage I, is impossible. The abraded process should be studied simultaneously on the microscale (matrix surface); and on the mesoscale (exposed aggregates). It leads to a change of the surface shape [13]. So here it is acceptable to use the mathematical tools of mechanics of frictional interaction [14-16]. Herewith we assumed that the pressure \( p \) and the speed \( v \) are constant. Then the concrete surface may be represented as an elastic half-space with the area \( \Omega \) strengthened in the circular domain \( o_a \) of the radius \( a \). The distance between centers of the strengthened zones along on one axis is equal \( l \). Application of this mathematical model for strengthened areas various geometric shapes (a square, an octagon, a circle) described in detail in [17-19]. Presented integrated solutions take into account both the geometrical parameters of the hardened areas and their number, and tribological characteristics of the material (hardening parameters and size of the hardened areas). The obtained numerical results had a good agreement with experimental data [17, 19].

4. Numerical simulation and results

Numerical image processing technique and parameterization modeling technique are most popular approaches in three-dimensional (3D) modeling the different material phase in concrete mixture. However, due to the difficulty of 3D mesostructure modeling and high computational costs, most of current stress-strain studies are two-dimensional (2D) models. In study of the abrasion process in stage III, the most interesting is the near-surface layer [20], so we modelled this layer as elastic half-plane with grains inclusions. In the 2-D mesoscopic simulation, the near-surface level represented as an elastic half-plane with the circular inclusions when the grain spacing \( l \), grain size \( a \) and protrusion height \( h \) (Figure 2, 3). To study the concrete abrasion in stage III as interaction between structure components we accepted that the real dynamical wear process of loading can be reduced to applying a static load on the grains. Thus, we fix the lower part of the half-space, and apply the load \( p \) to the half of the exposed part of the grains (Figure 2). The finite element method (FEM) is the most acceptable to apply toward the solution of such problems. All calculations were carried out by using ANSYS software [21]. PLANE182 is used for 2-D modeling of solid concrete structures.

| No. | E₁, 10⁶ Pa | v₁ | E₂, 10⁶ Pa | v₂ | a, mm | l, mm | P, 10⁶ Pa |
|-----|------------|----|------------|----|------|-------|--------|
| 1.  | 15         | 0.25 | 30         | 0.20 | 40   | 50    | 61     |
| 2.  | 20         | 0.25 | 30         | 0.20 | 40   | 50    | 61     |
| 3.  | 15         | 0.25 | 30         | 0.20 | 30   | 50    | 61     |
| 4.  | 20         | 0.25 | 30         | 0.20 | 30   | 50    | 61     |
| 5.  | 15         | 0.25 | 30         | 0.20 | 20   | 50    | 61     |
| 6.  | 20         | 0.25 | 30         | 0.20 | 20   | 50    | 61     |

In the present work, experimental and numerical investigations have been performed to stress-strain analyses around grains and to determine of expected failure zone locations. Six numerical experiments were carried out with different geometric and physical parameters of the cement-sand matrix and
grains. Parameters for a series of experiments according in [18] are listed in Table 1, where $E_1$ – Young’s modulus of matrix, $E_2$ – Young’s modulus of grains, $\nu_1$ – Poisson’s constant of matrix, $\nu_2$ – Poisson’s constant of grains.

The results of the numerical calculations of Equivalent Stresses (Mises) are shown in Figure 4 – Figure 9.

**Figure 2.** Graphical realization of the near-surface layer with the inclusion of grains.

**Figure 3.** $a$ – the grain size, $l$ – is the distance between the centers of the grains, $h$ – is the protrusion height.

**Figure 4.** Equivalent stress (Mises) for the matrix, experiment 5.

**Figure 5.** Equivalent stress (Mises) for the matrix, experiment 6.

An analysis of the graphs showed that the geometrical relationships are more affect at the formation of fracture zones of the adhesion boundary near of load application. Thus, as the grain size decreases and, correspondingly, the distance between them decreases, the stress value increases (Figures 6, 8). And conversely, the stresses decrease on the opposite side of the grain (Figures 7, 9). The deformation modules ratio to a lesser extent affects the magnitude of the stresses, but at the same time, the stress diagrams are more uniform when the difference between the modules decreases (Figures 6-9).

The results of determining the strain distribution in the matrix around the inclusions (not represented in this paper) made it possible to preliminarily determine the location of the fracture zones both a matrix, and in the boundaries between the matrix and grains. Analysis of the results showed that in a material with a weak matrix and a large distance between grains, the fracture begins in the near surface level. Conversely, with a grains size increasing and strong matrix, the destruction will occur at a certain distance from the surface, comparable to the grain size. These results are in good agreement with the results of experimental studies [11-13].
Figure 6. Graphs of Equivalent Stresses (Mises) experiment 5, 3, 1, in the corresponding nodes on the surface of the matrix.

Figure 7. Graphs of Equivalent Stresses (Mises) experiment 1, 3, 5, in the corresponding nodes on the surface of the matrix.

Figure 8. Graphs of Equivalent Stresses (Mises) experiment 2, 4, 6, in the corresponding nodes on the surface of the matrix.

Figure 9. Graphs of Equivalent Stresses (Mises) experiment 6, 4, 2, in the corresponding nodes on the surface of the matrix.
5. Summary
This paper developed a mesoscale finite element model for investigation of complex fracture in near-surface level of abraded concrete. The nucleation and propagation of microcracks and macrocracks in 2D half-plane is realistically modeled in detail with a few important conclusions drawn. The effects of coarse aggregate distributions on performance of concrete abrasion resistance are also evaluated.

6. References
[1] Itoh Y, Yoshida A, Tsuchiya M and Katoh K 1988 Proc. of offshore technol. conf. OTC 5687
[2] Saeki H, Asai Y, Izumi K and Takeuchi T 1988 Japan. The 20th Marine Development Symp.
[3] Laplante P, Alticin P C and Vezina D 1991 J. of Materials in Civil Engineering vol 3(1) pp 19–28
[4] Huovinen S 1993 Cement and Concrete Research vol 23(1) pp 69–82
[5] Papenfus N 2003 Sun City, South Africa. Applying Concrete Technology to Abrasion Resistance Proceedings of the 7th International Conference on Concrete Block Paving
[6] Kryžanowski A, Mikoš M, Šušteršič J and Planinek I 2009 ACI Materials J. vol 106(4) pp 349–356
[7] García A, Castro-Fresno D, Polanco J A and Thomas C 2012 Road Materials and Pavement Design vol 13(3) pp 534–548
[8] Horszczaruk E 2008 Wear 264(1-2) pp 113–118
[9] Møen E, Høiseth K V, Leira B and Høyland K V 2015 Cold Regions Science and Technology vol 110 pp 202–214
[10] Huovinen S 1990 Espoo, VTT Publications 62 (Doctoral thesis) 110 31
[11] Makarova N V 2008 Assessment of Reliability of Materials and Structures: Problems and Solutions: Proc. of the Intern. Conf. (SPb.: Polytechnic Univ. Publ.) pp 219–224
[12] Makarova N V 2009 Vestnik grazhdanskikh inzhenerov vol 3 pp 137–139 (In Russian)
[13] Makarova N V 2013 J. Appl. Mech. and Mater. vol 357 (Zurich: Trans Tech Publ) pp 1259–1262
[14] Goryacheva I G 2001 Mechanics of friction interaction (Moskva: Nauka) (In Russian)
[15] Slobodyan B S, Lyashenko B A, Malanchuk N I, Marchuk V E and Martynyak R M 2016 J. of Mathem. vol 215 (1) pp 110–120
[16] Goryacheva I G and Goryachev A P 2016 J. of Appl. Mathem. and Mech. vol 80 (1) pp 73–83
[17] Makarova N V and Polonik M V 2013 J. Appl. Mech. and Mater. vol 248 pp 355–360
[18] Makarova N V and Polonik M V 2012 Proceedings of the International Offshore and Polar Engineering Conference pp 67–71
[19] Makarova N V, Polonik M V and Rogachev E E 2012 Bulletin of CSPU named after I. Ya. Yakovlev. Series: Mechanics of limit state. Problems of Nonlinear Mechanics and inelastic deformation of solids vol 4(14) pp 164–173 (In Russian)
[20] Dhir R K, Hewlett P C and Chan Y N 1991 Materials and Structures vol 24(2) pp 122
[21] ANSYS Theory Reference. Structures. SAS IP, Inc.