Analysis and experimental evaluation of contact interaction of simple punch shapes with concrete

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Abstract. The article presents the results of the study of contact interaction of cylindrical, conical and roller-shaped punches with concrete. The stress-strain state of the material is assessed during penetration. The paper discusses how the angle of tapering of a simple punch shape affects the contact strength of the material. There are some hypotheses in the paper that describe the nature of the interaction of simple punch shapes with the material, there is a high convergence of the results with the main provisions of the mentioned hypotheses. In particular, it is found that the contact stresses in the area of contact of a punch with the material in areas significantly exceeding the strength limit of concrete can be characterized by the ratio of the strained volume of the material to the volume of the pressure bulb of the material. Its size is determined by the properties of the material.

1. Introduction

We are surrounded by the walls, the ceiling, the floors and other elements of buildings and structures that have long been an integral part of life. All of this was made up of materials, the durability and the safety of which are examined by the engineers long before building anything.

However, any construction site sooner or later ages physically or morally, or simply becomes unnecessary. Therefore, the elements of the structure require their demolition and disposal, which, in turn, require the use of special machinery and equipment. The existing machines and equipment made for demolition and disposal of building materials (concrete breakers, hydraulic hammers, multiprocessors) often become the subject of intuitive design or copying of such machines using minimal scientific justification of the design in terms of interaction with the material. It is possible to optimize and choose the suitable parameters of elements and systems of these machines based on the deep analysis of the working process of interaction of the working body with the material.

It is necessary to start the analysis of the demolition of a concrete product with studying the contact interaction of destructive elements with the material because at this exact moment the stress raiser is formed, contributing to the destruction, and at the same time, the body of the disposed structure accumulates stresses, which contribute to the formation and the growth of the crack. This process was already described by A.A. Griffith [1, 2] based on the energy approach to the formation and the growth of a new crack. Subsequently, E. Orowan and G. R. Irwin [3-5] pointed out that plastic strain significantly affects the formation of a new crack surface, resulting in a new concept of “fracture toughness”.

Any similar analysis is currently possible with known forms of stress raiser and the magnitude of these stresses. However, in the case of destruction of reinforced concrete structures with cutters or teeth of different shapes, the patterns of how the raiser and the stresses accumulate in the material under the
given load in the working body have not been studied to the extent necessary.

2. Reinforced concrete as a subject of destruction and disposal

Reinforced concrete is a multi-component material and, therefore, by definition, is a composite with a directional position of reinforcing rods, which, in turn, leads to a pronounced anisotropy [6–8]. Concrete is a matrix of the composite material and can also be considered as a dispersion-filled composite [9], consisting of fillers and a binder. Meanwhile, the properties of the filler and the binder are close to each other because both materials are a part of ceramics group with approximately equal durability and strain properties. Given that the scaling ratio of the elements of concrete macrostructure in relation to the size of a fracture is significantly large, concrete can be considered a homogeneous isotropic material in this paper.

Mechanical destruction of the reinforced concrete is conducted by destroying the matrix and separating its shattered elements from the rebar. The working body of a machine (a tooth, a chisel) penetrates the matrix, forming a stress riser in the concrete. With no analysis of the interaction of the material with the working body, it is impossible to predict the load required to fracture the reinforced concrete.

There are different approaches to describe the behavior of the material under the contact loads. For a perfectly elastic half-space, the contact convergence in the center of indentation of a conical punch can be expressed as follows [10–12]:

\[ h = \sqrt{\frac{\pi P (1-\gamma^2)}{2E \tan \varphi}} \]  

where \( P \) is the punch indentation force; 
\( \gamma \) is the Poisson ratio; 
\( E \) is the modulus of material elasticity; 
\( \varphi \) is the cone angle (the angle between the cone axis and its generatrix).

The penetration of an elastic half-space with a circular punch with a base diameter of \( d \) is expressed as follows [13–15]:

\[ h = \frac{P (1-\gamma^2)}{E} \]  

To determine the contact convergence in the center of indentation by a spherical punch with a radius \( R \), there is the following dependence [15]:

\[ h = \frac{3P (1-\gamma^2) R}{4E} \].

However, despite the almost non-existent plastic component of strains, the concrete exhibits non-linear properties [16] in the zone of elastic strains, and the stress-strain graph is a curve corresponding to the strain with hardening[17]. Therefore, it is impossible to use the equations (1), (2) and (3) in their pure forms.

Since it is poorly studied how the material functions outside its durability, there might be scientific value in exploratory tests to determine the specific aspects of contact interaction of a punch and material. The works of Professor Zelenin [18] expand upon the study of processes of cutting thawed and frozen soils with emphasis on exploratory tests. The study results proved to be useful and became mainstream for making new machines and the further development of soil cutting and digging theory [19, 20]. The work indicates that a pressure bulb appears in the contact zone of a working body, and this core significantly impacts the magnitude of soil cutting resistance forces. The formation of a pressure bulb during the indentation by a punch (figure 1, a), the shape of which is close to a cone with an angle between the axis and the generatrix equal to the angle of internal friction in the material \( \varphi \), occurs gradually, while accumulating some density. After that, the pressure bulb penetrates the material, while the deformation of the material around the pressure bulb and the internal friction of the material on the surface of the pressure bulb resist the punch indentation. A similar phenomenon is presented in the paper [21] in the form of the indentation of the asphalt concrete by a flat cylindrical punch.
Figure 1. Pressure bulb formation during indentation by various punches: a - a flat cylindrical punch; b - a conical punch with the angle of tapering greater than the angle of internal friction in the material; c - a conical punch with the angle of tapering less than the angle of internal friction; d - a spherical punch; e - a roller-shaped punch.

When the material is indented with a conical punch with the angle of tapering $\alpha$ greater than the angle of internal friction in the material, $\varphi$, the pressure bulb is also formed (figure 1, b). In the case when the cone has an angle $\alpha$ less than the angle of internal friction of the material $\varphi$, the pressure bulb is not formed, and the punch penetrates the material with the material covering the conical surface. The punch indentation resistance force is a vector sum of elementary friction forces and elementary material deformation forces. Given that the friction rate between the steel surface of the punch and the material is less than the internal friction rate in the material, the punch indentation resistance force is also decreased. After the increase of the angle of tapering of a conical punch when the sharpening angles become equal to the angle of internal friction in the material, an abrupt change of the force of indentation occurs.

There are similar processes in concrete, however, the destruction of the material with the appearance of local and main fractures can occur before the formation of a pressure bulb and after. The specifics of how the pressure bulb is formed, the stresses at its formation point and in the material, the shape of the bulb and the tooth affect the force required to destroy a slab of reinforced concrete.

3. Research problems and methods

The concrete strain in the area of pressure bulb formation takes place outside the durability of the material. There are non-linear elastic properties, bonds of the particles are breaking, and the structure becomes compacted. The theoretical description of this process with the necessary reliability level would require studying all aforementioned processes at a microstructural level, which involves a large amount of research beyond the scope of the task at hand. In the present research an experimental hypothesis assessment is proposed, which formulates the contact stresses on the punch surface $\sigma$ as a ratio function of the strained material $\Delta V$ to the initial volume of the pressure bulb $V$:

$$\sigma = f\left(\frac{\Delta V}{V}\right).$$ (4)

The study was conducted by indenting simple punch shapes: a cylindrical punch (figure 1, a), a spherical punch (figure 1, d) and a roller-shaped punch (figure 1, e). The indentation of various punches of various dimensions and shapes was carried out on a press (figure 2, 3, a). Punches 1 were mounted on the mandrel 5 and indented at different depths. Along with this, the strain shown by the indicator 4 and the indentation force measured by the sensor 3 were recorded. The concrete samples of medium strength branded B 22.5 (GOST 26633-91) were selected for the experiment.
Figure 2. Experimental press scheme designed to study the penetration process of the concrete samples with the punches of various shapes: 1 – replaceable punch; 2 – measuring system; 3 – force gauge; 4 – dial gauge; 5 – mandrel; 6 – straight-side press.

The parameter of the relative volume change $\Delta V/V$ takes a different value depending on the punch shape, its dimensions and the indentation depth $\Delta h$. The hypothesis expressed by the equation (4) must be universal and cover various shapes of the indenter tips. We would also like to note that this hypothesis is valid in the area of the greater position angles of the basic sites of the mentioned punch shapes to the direction of the punch movement than the angle of internal friction in the material. This restricts the depth of indentation of the spherical and the roller-shaped punches.

The geometric relation of volumes for a cylindrical punch after transformations can be expressed as follows:

$$\frac{\Delta V}{V} = \frac{6 f}{d} \frac{\Delta h}{d} \Delta h$$

(5)

where $d$ is the diameter of the punch, $f$ is the internal friction coefficient in concrete.

For a spherical punch, the ratio is:

$$\frac{\Delta V}{V} = \frac{12 \pi d h^2 (R - \frac{1}{2} \Delta h)}{\pi d^2 h}$$

(6)

where $R$ is the radius of the spherical punch, $d$ is the diameter of a contact surface of the sphere with the surface of the material.

A roller-shaped punch is different for its wedge-shaped pressure bulb. The volume ratio is expresses as follows:

$$\frac{\Delta V}{V} = \frac{\pi R^2 a - R^2 \sin \gamma}{b^2 \tan \phi}$$

(7)

where $R$ is the diameter of the roller-shaped punch, $b$ is the width of the contact surface of the roller with the concrete, $\gamma$ is the angle of contact of the roller with the concrete.

The contact stresses are determined by the indentation force and the contact surface projected onto the surface perpendicular to the load direction. The contact surfaces of the cylindrical and the spherical punches can be calculated as follows:

$$\sigma = \frac{4F}{\pi d^2}$$

(8)

The contact stresses of the roller-shaped punch can be found as follows:

$$\sigma = \frac{F}{b l}$$

(9)

where $l$ is the roller length;
In the course of exploratory tests the punches with the following dimensions and shapes were used for indentation: cylindrical punches with diameters of 1.5, 2.2, 4, 5, 8, 10 mm; spherical punches with diameters of 5, 9.6, 14, 27 mm; roller-shaped punches with diameters of 5, 7, 10 mm (figure 3b). Indentation had been conducted before the material started to fracture. Each punch was used to indent with five to seven repetitions. The results of the experiment, in which there were small chips on the surface of the concrete, were discarded and not analyzed.

4. Study results

Figure 4 illustrates the experiment results calculated for the concrete internal friction coefficient $f = 0.6$. In the course of the experiment we obtained the strain and the punch indentation forces. After processing the data we obtained the experimental dependence of contact stresses on the relative volume strains, the chart is presented in figure 3.

The graph shows the results reflecting the process of penetration by roller, cylindrical and spherical profiles. The graph does not show the results of pressing the conical dies, as the nature of the stress-strain state in the zone of sharpening can cause ambiguous results. In addition, depending on the angle of sharpening, nonlinear effects may occur due to the random nature of the value of the internal friction angle and the friction coefficient characterizing the interaction of the tip with the material.

The results reflect the adequacy of the presented hypothesis expressed by the equation (4). For a given material (concrete with a uniaxial compressive strength corresponding to the grade B22, 5), the volumetric deformations occurring under the die regardless of its shape, provided that there are no external friction processes in the contact deformation zone, are proportional to the contact stresses with a coefficient of proportionality equal to 470. The increase of contact stresses occurs when the pressure bulb is formed in concrete; this process is expressed as a linear function. The following expression is the regression equation that corresponds to the given chart for the given experiment conditions:

$$\sigma = 470 \frac{\Delta V}{V}.$$  \hspace{1cm} (10)

Regression confidence factor $R^2 = 0.827$. Given there is high heterogeneity of the properties of the volume material, the value of the regression confidence factor is quite high.

The parameter that takes a value of 470 in the equation (10) is a modulus of the volumetric strain for the given material and can be used in reverse engineering.

It is obvious that the work of the material under the influence of contact loads significantly exceeding the compressive strength of the material is well described by the linear function. This permits to predict easily enough the value of stresses in the volume of the material, developing as a result of the surface interaction of the working body with concrete or reinforced concrete (for example, using the methods of finite element analysis). Prediction of residual deformations also allows to reveal the shape of the...
stress concentrator in the area of contact of the working body with the material, which allows to analyze the processes of brittle fracture. In the aggregate, both possibilities determine the magnitude of the loads on the working body of the destroying machine.

![Graph showing contact stresses on relative volume strains of concrete during penetration with different punch shapes.](image)

**Figure 4.** Generalized dependence chart of contact stresses on relative volume strains of concrete during penetration with cylindrical, roller-shaped and spherical punches of various sizes.

This way of engineering analysis can be implemented not only for the tasks of determining the forces of resistance to destruction but also for the tasks of justifying the parameters of the equipment as a whole or optimizing its individual elements.

5. **Conclusion**
Exploratory tests conducted in this work allow us to draw the following conclusions concerning the contact interaction of simple punch shapes with concrete:

- contact stresses in areas of interaction of destructive elements of machines with concrete are significantly (up to 30…40 times) higher than the durability limits of concrete in uniaxial compaction of standard samples;
- the value of contact stresses affected by the destructive elements comes from the relative volumetric strain in a linear function. To analyze these stresses, a modulus of volumetric strain turns out to be useful.

The results of the experiment will allow us to analyze the demolition and disposal of reinforced concrete structures with working bodies of construction and road machines.

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