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Physical basis of destruction of concrete and other building materials

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Abstract. In the article the scientifically-grounded views of authors on the physical essence of destruction process of concrete and other materials are stated; it is shown that the mechanism of destruction of materials is similar in its essence during the mechanical, thermal, physical-chemical and combined influences, and that in its basis Newton's third law lays. In all cases destruction consists in decompaction of structures, loosening of the internal bonds in materials, in the further integrity damage and their division into separate loosely-bound (full destruction) and unbound with each other (incomplete destruction) elements, which depends on the kind of external influence and perfection of materials structure.

1. Introduction
The basis of materials fracture resistance is Newton's third law of motion–any external energetic effect on physical body always naturally resisted by the internal, volumetric energetically adequate reaction. As soon as the latter reaches critical value, namely, the integral value of inner bonds energy in material with specific structure, it destroys, i.e., is divided into individual elements, which are not connected or weakly connected with each other, which depends on material structural perfection and type of external effect. External power effect can be thermal, mechanical, physico-chemical and combined. The full, from physical point of view, destruction of any materials structure should be discerned – i.e. its decay to elementary particles, compiling its physical base, the bond energy between which reaches such critical values, when a solid body transfers to liquid state. Such type of destruction can be observed with heating material with any structure till melting.

2. Destruction of concrete when heated to high temperatures
Researches show that the most complete destruction of concrete and other materials from the physical point of view is apparently adequately modeled by the process going on when heating to high temperatures. The heating of solid bodies to high temperatures results in the more intensive heat motion of atoms of chemical elements, which compose the material, in the increase of distances and weakening bonds between them and, consequently, the strength of body. With the increase of temperature, the heat oscillatory motion grows; their deviation from neutral position and the distance between them increases, and therefore, the decompaction and deformability of materials increase.

   At last, when the amount of external energy applied to concrete reaches critical value, it transfers to liquid state, to the melt. Melting of a pure substance occurs at constant temperature, which is called melting point (t_{melt}). Melting of composites or mixtures of a certain charge makeup, including

concrete, occurs gradually in a wide range of temperatures. For example, when heating a mix of rocks, it gradually with the lowering of inner bonds energy, changes its state, i.e. transfers from elastic-brittle state (viscosity $10^{14}...10^{16}$ Pa×s) to viscoelastic state (viscosity 10^7 Pa×s, temperature till 1000 $^{\circ}$C) and then with temperature till 1400 $^{\circ}$C - to viscoplastic state (viscosity $10^6...10^2$ Pa×s), which is characterized by the presence of a solid phase in melting. With a further increase of temperature, the melt transfers to true liquid state (viscosity 1...1,5 Pa×s), when there is no solid phase in melt. Herewith, the result of solid bodies' destruction with heating is its transfer to true liquid state (melt), and the fracture surface in this case is much larger than with the destruction by external load. Therefore the energy of solid bodies' destruction when heating must be much higher than the energy of their destruction by external load, which is confirmed by calculation, made for heavy-weight concrete of B 60 grade with average density 2400 kg/m^3. The temperature of concrete melting is 1620°C. The amount of heat energy, needed for concrete melting, was calculated by the known formula $Q = cm\Delta t$, with specific heat of concrete 0.9 J/g×K. The obtained result was 3456 J/cm^3. The standard durability of concrete grade B 60 with durability variation coefficient 13.5 % is equal to 77 MPa or J/cm^3. That means that when heating this concrete till melting, 45 times more energy is needed than for its destruction by external loads. In connection with the above-mentioned, there is a reason to believe that consumption of thermal energy in J for melting one cubic centimeter of materials can to a certain extent characterize their potential capabilities. This is proved by the fact that the durability, calculated by the suggested method, for silicon (2935 MPa), silicon oxide (3654 MPa), aluminum oxide (5090 MPa), concrete of grade B 60 (3456 MPa), steel (15393 MPa) are almost theoretical, defined by other researchers and by other methods [1…3]. So, in accordance with works of Kuznecova T.V., Kudriashov I.V. and Timashev V.V. [4], the theoretical durability of ettringite crystal lattice is 3100 MPa and of low-basic calcium hydrosilicate– 2200 MPA, calculated by dependence $R = 0,1E$, the theoretical durability of B60 grade concrete is equal to 4000MPa and for reinforcing steel – 18000 MPa. Moreover, the calculated durability of, for example, silicon carbide (5892 MPa) is comparable with real durability of its fine fibres (3500...4000 MPa) and filamentary crystals (up to 14000 MPa). So, an important and objective characteristic of strength values and heat resistance is the quantity of heat energy in J, which is needed for transfering 1 cm^3 of materials into melt. The stronger the inner bonds in materials are, the more the heat energy is needed to be applied to them (heating to higher temperature) in order to decompact their structure enough and to lower the integral value of inner bonds energy to the value, which provides the transfer of material to the melt. From that point of view, the data about melting temperatures of some chemical elements and their compounds are useful. Analysis of the known chemical elements of the periodic table shows that the temperature of 4000°C can not be resisted by any of them. The temperature of 3000 $^{\circ}$C can be resisted by only some of them: wolfram (t_{melt} = 3380 $^{\circ}$C), osmium (t_{melt} = 3047 $^{\circ}$C), tantalum (t_{melt} = 3014 $^{\circ}$C) and rhenium (t_{melt} = 3190 $^{\circ}$C); the temperature 2000 $^{\circ}$C: boron (t_{melt} = 2074 $^{\circ}$C), niobium (t_{melt} = 2477 $^{\circ}$C), technetium (t_{melt} = 2200 $^{\circ}$C), iridium (t_{melt} = 2447 $^{\circ}$C), hafnium (t_{melt} = 2230 $^{\circ}$C), ruthenium (t_{melt} = 2250 $^{\circ}$C) and molybdenum (t_{melt} = 2620 $^{\circ}$C); the temperature   1500 $^{\circ}$C: scandium (t_{melt} = 1541 $^{\circ}$C), vanadium (t_{melt} = 1920 $^{\circ}$C), yttrium (t_{melt} = 1528 $^{\circ}$C), iron   (t_{melt} = 1539 $^{\circ}$C), chromium (t_{melt} = 1890 $^{\circ}$C), titanium (t_{melt} = 1668 $^{\circ}$C), rhodium (t_{melt} = 1963 $^{\circ}$C), platinum (t_{melt} = 1772 $^{\circ}$C), zirconium (t_{melt} = 1855 $^{\circ}$C) and palladium (t_{melt} = 1554 $^{\circ}$C). Oxides, carbides and composites can resist even higher temperatures as compared with original materials. For example, silicon oxide has melting temperature 1728 $^{\circ}$C, aluminum oxide – 2044 $^{\circ}$C, carborundum – 2830 $^{\circ}$C, magnesium oxide – 2825 $^{\circ}$C, boron carbide – 2450 $^{\circ}$C, zirconium carbide – 3800 $^{\circ}$C, zirconium oxide – 2700 $^{\circ}$C , boron nitride – 3200 $^{\circ}$C, the composite of carbon fibres have heat resistance to 2500°C, ceramic fibrous products on the basis of kaowool and fireproof clay

can resist temperature 1100...1700 $^{\circ}$C, chamotte products have heat resistance to 1580..1750 $^{\circ}$C, depending on product class.

High-refractory concretes on high-aluminous cement (aluminum oxides content - no less than 75 % and iron oxides content - not more than 1 %) on aluminum phosphate mix (corundum with add of ortho-phosphoric acid), on periclase cements (content 85 % and more) have heat resistance more than 1770 $^{\circ}$C and so on. As follows from the above mentioned, for all earthly solid materials, the limit temperature, which they can resist is 3000 $^{\circ}$C. When heating them with higher temperature, all of them stop being in solid state. Thus, the fundamental pattern of destruction of all solid natural and artificial materials with heating to high temperatures is only one – their transfer to liquid state. But before melting in real concrete decompaction, defect of structure continuity, connected with its imperfection, and lowering of its durability occur. With heating of heavyweight concrete on Portland cement to more than 400 $^{\circ}$C, the material structure is damaged, which is connected with dehydration of cement stone minerals, with different coefficients of thermal expansion of components of cement stone and concrete, with decomposition of $Ca(OH)_2$ at temperature 547 $^{\circ}$C, and $CaCO_3$ at 600 $^{\circ}$C, with modification transformations of quartz at temperatures 575 and 870 $^{\circ}$C and increase of its volume, with the increase of steam pressure in material pores and other factors. Of course, all the above described processes, which occur in concrete, lead to origin and development microcracks and other defects in the structure of material. As a result of heating to 1200 $^{\circ}$C, the concrete durability is only 35 % of the original. If the same concrete is later cooled to 20 $^{\circ}$C, it loses its residual durability completely due to CaO hydration. Therefore the addition of special additives (fine-ground chamotte, granulated slag, fly ash and others) into the composition of concrete on Portland cement increases the heat resistance of concrete, because at high temperature CaO fuses with these additives and due to that, the durability of material increases. In relation to other materials, there can be other reasons of destructions of their structure at heating. But if the required starting raw material and its optimal composition are selected professionally, the concrete heat resistance of 2000 $^{\circ}$C and higher can be achieved.

3. Technical opportunities of concrete and other materials

The partial destruction of materials with real defective structure is their incomplete separation into individual comparatively large parts, each of which has enough durability and their size is defined by the extent of perfection and homogeneity of material structure. That type of destruction happens at the effect of external load on real materials or (and) under the physico-chemical effect of the environment. Due to the not uniform strength of all inner bonds between components in materials with defective and heterogeneous structure, they are destroyed in most weak places. Elements of samples with the strongest inner bonds remain not destructed; into these parts the materials are further divided. With increase of perfection and homogeneity of structure, all inner bonds in materials become equal, and during destruction they disintegrate into smaller parts. As a result, the limit of technical capabilities of concrete and other materials is determined with such critical amount of the applied energy, after reaching which the full destruction of materials with their transition into another state occurs, particularly, their decay to individual elementary parts, composing the physical base of materials, comparatively weakly bound with each other and representing a liquid substance like melt, and at incomplete destruction. the spontaneous separation of samples to relatively large parts, each of which has its own durability, begins [5…10].

In accordance with physics laws, repulsive forces between atoms of chemical elements in materials have almost unlimited values, while attractive powers between them are limited and therefore they are the weakest link in material structure. That means that durability and deformability with tension play the main role in concrete destruction and other materials with any types of external effects, including the thermal exposure. Durability is defined by the weakest component of structure – integral value of inner bonds energy in materials with specific structure that is with inner forces of adhesion of components with each other, which characterize the tension durability. Lowering the inner bonds in materials to the critical value by heating them to high temperatures happens under the action of heat energy, and their rupture with the effect of external force – under the effect of mechanical energy, in

particular, with the effect of tensile or shearing loads. However, the shear strength is much higher than ultimate tensile strength. Thereby, it is most likely that the breaking of inner bonds, the damage of integrity of materials structure occur because of the excess of load on ultimate tensile strength. The further crack propagation happens by both tear-off and shearing mechanisms. It was established that at the effect of any external, including one-axle, load on materials, a compound stress arises. For example, under the effect of external one-axle stretching force to material, the stretching deformations and stresses arise in it, calculated from external load, and simultaneously volumetric inner stresses arise as well, which constrict material as resistance response to external loads. That means that tensile stress in materials is determined by inner attractive forces between atoms of chemical elements, their components, which arise as a result of displacement in the direction of moving of elementary parts from their first energy-effective location. By analogy, with external one-axle compressive load in materials the compressive deformations and stresses arise, calculated from external load, and simultaneously volumetric inner dilative stresses arise as well, which are determined by inner volumetric repulsive forces between atoms of chemical elements, due to dislocation of elementary parts from their first energy-effective location in direction of approach. If external compressive force is volumetric and uniformly distributed, the arising of inner volumetric repulsive forces between atoms of chemical elements provide material with high, ideally unlimited durability. If external compressive load on material is one-axle, so these inner volumetric repulsive forces will resist external compressive force in direction of its action and simultaneously are the main reason of material destruction in other materials, where there is no external resistance, which is confirmed by the test.

In the course of experiments, a polymer mortar ball with diameter 70 mm and density = 1760 kg/m^3 was tested by vertical compression on 10 tons press (fig. 1).
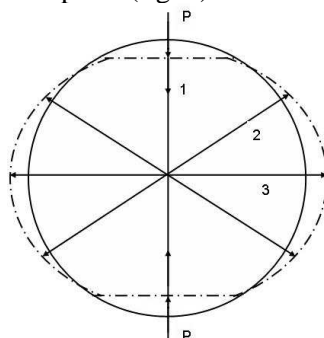
Figure 1. A diagram of test and deformations distribution of a polymer mortar ball at one-axle vertical compression; 1, 2, 3 – directions of deformation measuring

The compression deformations of the ball were measured by caliper and deformation in other directions - by micrometer. The results are shown in table 1.

Table 1. Results of the polymer mortar ball tests

№	Load, t	Absolute deformation of ball, μm, in direction		
		1	2	3
1	6	700	27	113
2	7	900	39	131
3	8	1500	87	199
4	9	1900	96	289

The results of experiments (table 1, fig. 1) confirm that the external one-axle vertical load on ball cause the inner, volumetric dilative stresses, which counteract external compressive load in direction of it effect and in other, not only perpendicular to direction of effect of external load directions, create volumetric deformations of extension, which are seen in the picture.

If the structure of material is ideal, at the mechanical effect its full destruction is theoretically possible.

In material with ideal and uniform structure all inner connections between atoms of chemical elements and components are ideally stable and of equal strength and with the reach of limit of theoretical durability, they break instantly and simultaneously. Therefore with the destruction of material with ideal structure by external load, it has to be theoretically divided to separate atoms of chemical elements, that is, to transfer to the gas form, which is hardly probable by physics law. Transferring from solid to gas form is only possible for artificially made materials, which can not exist in normal earth conditions (artificial ice, naphthalene and some other). It is also possible to remove water and gas from the material, before melting it, for example, at carbonates decomposition, but such materials as rocks, which exist on earth for million years, can not transfer at once from solid to gas form, omitting the liquid phase. With the increase of external effect, the energy of inner bonds in materials gradually becomes lower, so by physics laws, materials have to transfer gradually into liquid state and then to gas from. The state of substance is determined by the quantity of energy, which connects components in the whole unit and the bond strength. For the gas form of substance, the bond energy between molecules is 8...16 kJ/mole. If the bond energy is by an order greater, it is the liquid state of substance, if by 3 orders greater – it is a solid body. The most obvious changing of substance state under the effect of pressure or temperature appears in gases. For example, carbon dioxide in normal conditions appears in the gas form. But when applying a certain pressure on gas (for example, more than 5,85 MPa at room temperature) and bringing together its molecules on such distance, so that the energy of bond between them reaches its critical value, the gas transfers to liquid. At the atmospheric pressure and cooling of CO_2 to critical value (lowering its inner energy) the gas transfers to solid state (artificial ice). The opposite process happens at temperature 78.5°C. So, by changing of distance between atoms and molecules of chemical elements and the energy of their interaction by any way (thermal or mechanic), we can transfer materials from one state to another. Therefore at the effect of external load and the reaching of theoretical durability, a material with ideal structure will apparently transfer to liquid state, which will be final result of its destruction, so it will be divided to individual atoms, ions, anions, cations, radicals and other elementary particles, weakly connected with each other and representing a substance of liquid nature with melt characteristics. In a similar way, the process of material destruction runs at physical-chemical effects on them, for example, multiform aggressive factors. Here we also can see the same destruction features, such as material decompaction, weakening of its inner bonds and increase of its deformability, break of integrity structure, lowering of durability and decay to parts, but for that the energy of chemical reactions, physical processes, bacterial activity and microorganisms and so on is spent, as described in the work.

4. Conclusion

On the base of the above-mentioned data and other researches a conclusion can be made that the mechanism of destruction of concrete and other materials in all cases is similar at heating, physico-chemical, mechanical and combined effects. The process starts with decompaction of material structure when the distance between atoms of chemical elements grows, the inner bonds between them are weakened and the deformability increases. The external effect on material grows, the decompaction grows, and the inner potential abilities become lower and in materials with real structure the break of their continuity starts, connected with the appearance of microcracks and other microdefects. As soon as quantity of external destructive energy or volume of microdestructions for real bodies reaches critical values, i.e. the limit of strength or of the integral value of inner bonds energy in materials is reached, their potential opportunities of destruction resistance become exhausted and the samples are divided to individual parts.

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