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Durability as integral characteristic of concrete

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Abstract. The carried-out research provides insight into the internal bonds energy in material as the basis of its durability, deformability, integrity and resistance to different factors (combined effects of external loadings and (or) environment), into the limits of technical possibilities, durability and physical reality of the process of concrete deterioration, which allows designing reliable and cost-effective ferroconcrete constructions for different purposes.

1. Introduction

Durability is a key indicator of concrete quality, which determines reliability and cost-effectiveness of concrete and ferroconcrete products, constructions and structures.

This research [1…3] has shown that durability is an integral characteristic of concrete, which assesses the material as a whole, from generation of a solid body to destruction resistance. The existing definition of concrete durability as an ability to resist destruction or irreversible deformation from external forces effect or internal stresses and environment is not correct and does not explain the essence of this phenomenon. The durability of concrete is not an ability of material to resist destruction; this is an ability it gets due to durability. In fact, durability is the main characteristic of concrete, which is defined by value of stable inner bonds between components and its structure, which provide the integrity of material, its identity to itself and ability to resist destruction or irreversible deformation by the effect of different factors (external forces and (or) environment). In fact, the actual durability of concrete is an integral value of inner bonds energy in material with concrete structure. Thereby, durability of concrete can be measured not only in MPa, but also in J/cm^3, which is, in the authors' opinion, more correct, because the essence of this feature is more precisely reflected. Concrete with ideal structure has to reach theoretical durability, which is significantly higher than the real one. In accordance with this research, the bond energy between atoms of chemical elements in concrete can be measured by elastic modulus, which in fact is the stress, which arises in a single section of material at relative dislocation of atoms or molecules from their optimal position, which equals one, if the Hooke's law is not broken and the sample is not destroyed. So, elastic modulus can be used for calculation of theoretical durability of concrete. According to different researches, the theoretical durability of different materials is 5 – 20 % of their elastic modulus and on average amounts to 10 %. With that in mind, the value of theoretical durability of concrete, for example, of concrete grade B60, is on average 4000 MPa (J/cm^3), and actually it is 77 MPa (J/cm^3) with a durability variation coefficient of 13.5 %. The difference is substantial and connected with considerable defects and differences of concrete structure on microlevels and macrolevels, which can be assessed by relation of the theoretical durability to the real one. The higher is this ratio, the more imperfect the structure of the material is.

2. Durability as an objective general quantitative value of the existence of different forms of substance

The value of durability is assessed by ultimate strength. The ultimate strength of concrete is defined by the load and the specific mode of its application in which the value of micro destructions in material becomes critical, after which spontaneous separation of samples into parts begins, each of which has certain durability. The critical value of microdestructions in concrete is assessed by the value of work, which is needed for destruction of material of unit volume «A_p» [1]. On the basis of this definition, the ultimate strength depends on load application mode. This means, that depending on modes with which examples are tested, one and the same concrete can have different values of ultimate strength. To eliminate uncertainty and set the single ultimate strength for all, which is used for practical purposes (design of constructions, comparative evaluation of different concretes and so on), the test mode of concrete samples is regulated by GOST 10180, in accordance with which the standard ultimate strength of concrete with rate of load application 0.4…0.6 MPa/s is determined.

With the raise of load application rate, the ultimate strength also rises, and with reducing it – slows down and reaches the long-term strength of concrete. The limit of technical capabilities of concrete can be also assessed by value of per-unit work «A_p», which has to be expended for reaching the critical value of microdestructions in material, after which the spontaneous separation of samples to individual parts begins, each of which has definite durability. The value of «A_p» can be calculated by the formula:

$$A_{\mathrm{p}} = \int_0^{\varepsilon} R d\,\varepsilon$$

The analysis of experimental data of many scientists shows that with changing of test mode of samples, the durability and the breaking strain value of concrete also change, but in such a way, that with acceptable error «A_p» is a constant value for a certain type and mix of concrete and type of load on condition of no strengthening in time, and it does not depend on samples test mode. It means that at any load application modes on certain concrete samples, they are destroyed only when they reach the maximum value «A_p». Another type of non-strengthening concrete of specific composition, other things being equal, will have its own limit of technical capabilities, which will grow with its strengthening [1].

Assuming that durability is an integral value of inner bond energy in solid body, it means that durability is an objective general quantitative measure of existence of different forms of substance. The state of substance is measured by amount of energy, which binds components into a single whole, and by the strength of this binding. If, for example, the value of bond energy of basic minerals of cement stone $3CaOSiO_2$, $2CaOSiO_2$, $3CaOAl_2O_3$, $4CaOAl_2O_3Fe_2O_3$ and $3CaOAl_2O_36H_2O$ is respectively equal to 5239.2; 4139.3; 6246.6; 9715.5 and 12062.4 kJ/mole, it is a solid state of material. If the bond energy between molecules is 40…80 kJ/mole, it is a liquid state of material. If the bond energy between molecules is 8…16 kJ/mole, it is a gasiform state. The bond strength between elementary particles in solid body is 3 orders greater as compared to the bond value between molecules in gasiform state. So, if between atoms of chemical elements the correct level of bond strength is not reached, the formation of solid bodies is not possible. That is why durability is not a criterion of solid body formation. If there is durability – then all the elementary particles, contained in material, are bound by durable chemical and physical-mechanical connections into a whole, a solid body with all its properties. If there is no durability, so there are no connections between elementary particles and there is no solid body.

3. Durability as a reliable criterion of the destruction degree of material structure and its residual potential capabilities

With acquiring integrity and durability, concrete gets ability to resist different destructive factors, which try to destroy bonds between elementary participles, and the internal energy between them, which determines its durability, prevents it. Concrete and cement stone are considered as extremely defective spatial systems, consisting of a large amount of chemical elements compounds, dissimilar by nature, properties and sizes, bound inside and between themselves by unequal chemical and physical-mechanical bonds. But the main role belongs to chemical bonds, because concrete is a waterproof and strengthening in time material, which is possible only with the prevalence of chemical bonds. In accordance with strength of materials science statements, if to any solid body a uniaxial vertical compressive load is applied, there are no any stresses in material in horizontal direction, so it is not taken into account that the structure of material responds to external loads and resists to them. In contrast to that, O.Y. Berg, Y.V. Zaycev and other scientists on the basis their researches assert that in this case there are horizontal tensile stresses in concrete, which are the reason of its destruction. In the authors' opinion, the tensile stresses, perpendicular to the uniaxial vertical compressive load cannot appear in material because in this direction there are no any tensile stresses in the given example. The carried-out researches show that in reality everything is somehow different, if one takes into consideration how the complicated physical structure of material resists to loading, and which are the bases and patterns of this resistance. If a system is not affected by load, it is in equilibrium state. As soon as under the effect of external forces the structural elements of system move from their energy-effective location, an internal volumetric stressed state of contraction or expansion arises with the action of compressive or tensile stresses, that is an adequate reaction of resistance to external load appears in the material structure instantly. Thereby, the structure of a solid body like concrete always actively resists to external loads. Regardless of the fact if there is one-axle, two-axle or three-axle load, a volumetric stressed state of contraction or expansion as a result of interaction between elements of the structure always arises in it [1]. High stresses are concentrated in defective or weakened places of concrete with the increase of load level. They reach such values, with which the bonds between elementary participles are broken, the material structural integrity is damaged, and the microcracks appear. The place of the first microcrack and the distribution of microcracks on material are determined by probabilistic laws. Where microcracks appear, the stresses decrease and relocate to different, less loaded structural elements, which stimulates the appearance of microcracks on nearby sites and so on, that is with appearance and progress of microcracks, the stressed state in concrete structure changes dynamically. With the rising of load and the time of its effect, the amount and sizes of microcracks also increase; some of them merge with each other and, as a result, the whole volume of samples is divided by combined microcracks into weakly connected between each other microvolumes, which weakens their load resistance. The carried-out experiments, in which cubes 10×10×10 cm, made of mortar of composition 1:1 = C:S (by mass, W/C = 0.4), in the as-formed state were cut in two or three parts, confirm it. After hardening in laboratory conditions within 20 days, they were tested in such not integral state, that is, with artificial vertical heightwise cracks, for compression by standard methods with test samples (solid cubes). The results of tests showed, that the durability of cubes, divided by artificial cracks into two or three parts, is lower than the durability of test samples by 18…30 and 26…50% respectively. This means that if concrete examples are disconnected by solid vertical cracks into two or three parts, they can resist external load in such condition, but on the whole their ultimate strength falls by 18…50% depending on the moment of cutting samples into parts. As the research has shown, in concrete with heterogeneous structure on micro- and macro-levels, stresses in the section, perpendicular to the direction of external compressive, for example, one-axle load, for obvious reasons are allocated irregularly – in some parts they are bigger, in other parts lower. This difference can be significant, especially with substantial difference between physical-mechanical properties of materials in nearby areas (for example, granite aggregate – cement stone, crystal and gel components of cement stone and so on). In accordance with statements of mechanics of materials, with such scheme of load the shearing failure is possible. So, in the loaded heterogeneous concrete structure all preconditions are created for shearing stress appearance in large amount of microvolumes and for the development of microcracks in this place (interface) and - by shearing mechanism - in all levels of structure, which is confirmed by experiment [2, 3]. Under the action of one-axle compressive load on concrete along with the expanding the considerable compression is observed because compressive stresses are many times larger than the expanding ones, so it results in the volume contraction of samples. Concrete is also a capillary-porous body, and therefore the material is compacted due to collapsing of pores and capillaries, closing of cracks and discontinuities, concrete creep and so on. For these reasons with the increase of compressive load, the reduction of volume of, for example, the cement stone until the destruction of samples is observed [4]. Concrete acts similarly until a certain level of load, when material reaches the maximum density and minimum volume, after which the decompaction and increase of volume [5] are observed. It can be assumed that with one-axle tensile load, the pattern would be different. With the further increase of load, microdestructions grow by the above-mentioned laws, interact with each other in volume of concrete and form a general destructive process, which goes with certain speed, and as a result of which, the elements of structure are formed, into which the material is finally divided. As soon as the volume of microdestructions reaches the critical value the concrete disintegrates into separate parts.

With the constant continuous load acting on concrete and in the process of non-elastic deformation, the sizes and volumes of the appeared microcracks increases. If the acting load does not exceed the long-term strength of concrete, the volume of microdestructions in material does not reach its critical volume and the destructive process gradually ends. If the load exceeds the long-term strength of concrete, then in the process of long deformation, the volume of microdestructions in material after a certain period of time reaches its critical volume and the material is destroyed. The higher is the level of load, the smaller time is needed to reach the moment of concrete destruction. The external load, under which the volume of microdestructions in concrete after the long required period of time reaches its critical volume, is called the long-term strength of the concrete. The long-term strength of the concrete depends on many factors, including its deformability. Thus, for a polymer-concrete, which has the increased long deformability, the ultimate long resistance equals (0.5…0.6) $R_{multiple}$ (depending on the type of binder) and for cement concrete with lower deformability - (0.75…0.85) $R_{multiple}$ [1].

From Griffiths to the present time, the destructive process has been assessed by the total critical length of microcracks, after reaching which concrete divides into parts [3]. But every crack in the moment of its formation has length, width and height. These parameters in equal measure influence the material destruction. Therefore the volumetric destructive process cannot be assessed only by the length of microcracks, because even with one-axle external compressive load on concrete, internal volumetric stressed state of expansion arises, which influences the genesis of microcracks in three directions - length, thickness, depth, and volume in general. Therefore it is more reliable and reasonable to assess process of concrete destruction by the volume of microcracks or microdestructions, which can be characterized by specific work, needed for destruction of material «A_p».

For real concrete the process of its destruction is volumetric and temporary, it is not instant, but developing in time with certain speed. Thereby, as is confirmed by the tests, with the increase of uniformity, durability and with the lowering of the amount of defects in the concrete structure, the lower and upper limits of microcracks formation increase, so the duration of destructive process is reduced. From theoretical point of view for concrete with ideal structure and homogeneity, the destructive process should be also volumetric, but instant, that is the destruction of samples should occur with the reaching of theoretical durability instantly in the whole volume.

As it is known, the shape and sizes of samples have great influence on concrete durability and type of concrete destruction. The smaller samples show greater strength, and prisms – smaller strength than cubes. At the same time, prism strength shows the concrete strength in constructions more reliably, because the bearing friction of a sample with press plates is excluded, and in fact, a prism is a construction, closer by shape to piles and columns. That is why prism strength is used in calculation of concrete and reinforced concrete products. But while researching concrete durability as a material, it is more correct to use standard cubes, because in test with prisms not only concrete durability without influence of bearing friction, but also the strength of constructions with certain shapes and sizes is determined. The destruction of structures often occurs on one plane. So, the shape and size of prisms have influence on results of durability determination and on the character of material destruction, which is not desirable. Additionally, durability and homogeneity of concrete, the mode of load application and other factors also have influence on the character of samples destruction. In the carried-out experiments for testing standard concrete samples with durability about 150 MPa with standard method, they always disintegrated at their destruction into many parts of medium size. In view of the above, one cannot agree with conclusions that the destruction of concrete samples ends with formation of one main crack. This variant is possible under certain conditions, but manifests itself mostly at constructions destruction. Another character of destruction is observed during the test of standard cubes without and with bearing friction, especially made of high-strength concretes. So, it is more correct to talk about formation of several significant cracks on concrete cubes, which divide samples into parts, or, even better, about the fracture surface. Since destruction always happens in the weakest places, the fracture surface outlines these places and divides material into elements of structure with less presence of defects and greater strength.

As it is noted above, the concrete integrity, self-identity, ability to resist destruction from the effect of different destructive factors is achieved by its durability. If concrete has sufficiently high integral value of inner bonds energy, stable in given conditions, low-defect dense structure, it will successfully resist any effects, which is confirmed by the research of scientists [2, 6, 7, 8]. It is experimentally found that in comparable conditions between W/C, frost resistance, corrosion resistance and concrete durability a similar dependence exists – with the lowering of W/C, the concrete durability and resistance in conditions of freeze effect, corrosive medium and other factors increase. So, durability of concrete is a criterion of assessment of the state of concrete and reinforced concrete structures, which work in different conditions: alternate moistening and drying, freezing, defrosting, effect of corrosive medium. It is the only reliable and direct criteria, which allows judging about the degree of material structure destruction and its residual potential capabilities.

4. Conclusion

Concrete operates in different conditions, which have significant influence on it. In normal conditions, the concrete durability grows, and in corrosive medium it becomes lower. The normal environment is such conditions, which are good for material strengthening. In this case, one may talk about concrete durability. The corrosive medium is such conditions, which destroy concrete. In this case, one may talk about frost resistance or corrosion resistance of concrete, but its state is estimated by changing of durability. That approach, in the authors' view, is contradictory and incorrect. In all cases, let us talk about concrete durability, but work in different conditions: in normal, chloride, alkaline, carbonic, magnesium medium and so on. So it is more correct to talk about concrete durability in normal conditions, about its durability in conditions of sea water, frost or corrosive medium. The assessment criteria of concrete state with complex effect on it of external and internal factors can be a certain standardized durability, which ensures the grade of concrete with corresponding durability variation coefficient, which should be rigorously followed in all cases. Whatever factors effect on concrete at the same time (load of different type and mode, corrosive medium, frost, radiation and so on), concrete durability in constructions must not be lower than the standardized one up to the end of designed useful life, which can be effectively provided. Then, the useful life period of buildings and constructions will rise to few hundred years.

Thereby, the actual durability of concrete is the integral value of inner bonds energy in material with real structure; it is a criterion of formation and assessment of concrete condition, basis of its ability to resist any destructive factors; it defines patterns of destruction and technical abilities of material, particularly its longevity.

References

[1] Gladkov D I, Suleymanova L A, Nesterov A P 2005 Strength as an integral characteristic of concrete. *Proceedings of the International Conference on Cement Combinations for Durable Concrete International Congress - Global Construction: Ultimate Concrete Opportunities. Cep. "Cement Combinations for Durable Concrete - Proceedings of the International Conference"* (University of Dundee, Concrete Technology Unit. Dundee, Scotland) pp. 701-707
[2] Suleymanova L A 2007 Energy of connection as the basis of constructional and exploitative characteristics of concretes. *News of higher educational institutions. Building.* **9** 91-99
[3] Suleymanova L A 2002 Energy of inner connections in material – basis of its durability, deformability and resistance to different factors. *Herald of Belgorod State Technological University named by V.G.Shukhov* **6** 154-159
[4] Bazhenov Y M 2002 *Technology of concrete*. (M.: ASV)
[5] Zaycev Y V 1982 *Design of deformation and durability of concrete by fracture mechanics method.* (M.: Stroyizdat)
[6] Makridin N I 2000 *Structure and parameters of cracking resistance of cement composites*. (Penza, PGASA)
[7] Gvozdev A A 1978 *Durability, structural changes and deformation of concrete*. (M.: Stroyizdat)
[8] Sheykin A E, Dobshic L M 1989 *Cement concretes of high frost resistance*. (L.: Stroyizdat)
[9] Moskvin V M 1980 *Corrosion of concrete and reinforced concrete, methods of their protection*. (M: Stroyizdat)
[10] Moshanskiy N A 1951 *Density and durability of concretes*. (M.: Gostroyizdat)