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STRENGTH DEVELOPMENT DYNAMIC OF CEMENT PASTE: TESTING AND CONTROL

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ABSTRACT

Compressive strength obtained from uniaxial test of concrete samples cured for 28 days under standard conditions is the basis for designing concrete structures. To design and construct concrete structures, one needs to know not only the strength of the material but also the full σ–ε function and its development history. The computerized DNW (Dynamika Narastania Wytrzymałości) testing system was designed specifically to examine material strength development. The system assures objective results and high accuracy of σ–ε function regardless of the age of the test sample. The study also offers examples of σ–ε functions and results of strength development research. *© 1998 Elsevier Science Ltd*

Introduction

Compressive strength obtained from uniaxial test of concrete samples cured for 28 days in standard conditions is the basis for designing concrete structures. However, it is necessary to remember that concrete is a maturing material and its properties depend on many factors. The strain of concrete elements generally is a function of six groups of factors: 1) composition of concrete mix; 2) performance technology (preparing the mix, casting, and curing); 3) age; 4) loading history; 5) loading conditions (testing conditions); and 6) stress level. To decrease the number of variables, technical standards require that the properties of concrete be determined through a uniaxial test in which test samples made and cured under fixed conditions are subject to simple compression. Under these limitations, the concrete properties (understood as a strain–stress relation) depend on three groups of factors: 1) mix composition; 2) age of concrete; and 3) loading conditions.

With this in mind, the experimental method of determining the properties of concrete should take the following three requirements into consideration.

Objectivity

Group C includes factors that do not, in fact, depend on the properties of material. Therefore, the fundamental requirement imposed on the measuring method is that test results must be independent of the factors introduced by the method itself. We will call this requirement "method objectivity." In the case of testing the strength of concrete, the matter is complicated by the fact that the very idea of strength is defined imprecisely, and the specifics of every known research method (procedure) influence test results. We will therefore consider a method objective if it guarantees identical results from testing different samples of a perfectly homogeneous material.

Accuracy

One should stress that the results of concrete strength tests usually vary greatly—the smaller the samples, the more varied the results. On the other hand, rapid technological development associated with the application of chemical admixtures requires intensive examination of the effects of these admixtures. First of all, cement paste samples should be tested. The obvious advantage of using such samples is their small size and low weight. However, the possibility of investigating the admixture in its most distinct and intensive form—without the obscuring influence of aggregate—is of utmost importance. Consequently, the growing need to conduct tests on small samples stresses the importance of precision.

Full Examination of Properties

Contemporary concrete technology more and more frequently requires not only the information on the properties of 28-day-old concrete, but also the properties of concrete during the entire period of maturation. Research on young concrete currently is seeing a particularly dynamic growth (1,2), largely connected with growing interest in thermal stresses due to cement hydration. This interest creates a need for a method that would allow for examination of concrete properties immediately after casting. Moreover, the requirements for some tests are increasingly demanding. Minimum requirement for determining mechanical properties of the material is defined by the relationship between stress and strain:

$$f(\sigma,\varepsilon) = 0, t = 28 \text{ days},$$

along with the postpeak behavior. This function, called in research laboratory “stress–strain function” (or σ–ε function), in the theoretician’s workshop is referred to as “constitutive law.” But due to an intensive change of the properties of concrete over time, the constitutive law should be constructed based on the following function:

$$F(\sigma,\varepsilon,t) = 0, t > 0,$$

which we will call full characteristic of material. To determine this function, it is necessary to conduct research in the postpeak state as well as to test samples regardless of their age.

With these three assumptions in mind—the need for objectivity, precision, and the examination of properties regardless of the sample’s age—a computerized system to investigate the dynamic of strength development (Dynamika Narastania Wytrzymałości [DNW]) has been constructed at the Building Research Institute in Warsaw.

Loading Conditions in Uniaxial Compression Test

Designing the DNW system was preceded by analysis of all factors comprising the overall loading conditions (group C). The following factors are included:

1. Shape of the sample’s cross-section (circular or square),

2. Sample's diameter-to-height ratio,
3. Sample's size,
4. Sample's diameter-to-maximum-aggregate-grain-diameter ratio,
5. Direction of compression (coaxial or perpendicular in relation to the direction of casting)
6. Loading rate,
7. Type of machine drive (dynamic or kinematic),
8. Rigidity of strength machine,
9. Conditions of contact between sample and strength machine, and
10. Eccentricity of load.

The problems of research technology are subject of both fundamental monographs devoted to concrete (3–5) and state standard [in the United States (6–8), Great Britain (9–11), and Poland (12–14)]. In general, factors 1, 2, and 3 are taken into account by application of correctional coefficients. The use of samples greater than a multiple of maximum aggregate grain diameter [in the United States—3 (6), Great Britain—4 (10), and Poland—3 (14)] eliminates factor 4. Factors 5 and 6 usually are omitted as negligible; it is not always right, and the standards require normative loading rate and compression direction.

Factors 7 and 8 usually are beyond the researcher's control, because the researcher is limited by access to a particular testing device. However, one must bear in mind that a dynamic drive of strength machine or a machine that is not rigid enough makes it impossible to examine the phenomenon of softening. To examine σ–ε characteristic along with the postpeak part, one has to use a machine in which the traverse can maintain constant speed regardless of the sample's resistance. That is why the phenomenon of softening has been examined only since the 1960s (15–17).

Of the 10 factors, factors 9 and 10 are critical for the accuracy of tests; they seem fully dependent on the researcher's precision, but once the technology of research is decided upon, the researcher is, to a large degree, helpless. Contact conditions between sample and testing machine largely depend on the smoothness and flatness of the sample's surface (we omit the use of washers and leveling layers). The subject is well researched, and it is known that 0.25-mm deviation of the sample's surface from a plane can decrease its strength by about one third (4), whereas differences in friction coefficient for the sample and the machine's plate depend on the sample's resilience and its height-to-diameter ratio. In practice, these differences do not exceed 10%, and the theoretical difference in strength caused by a change in the value of friction coefficient from 0 to infinity for cube samples is 23% (18).

The matter of load eccentricity remains practically untouched in the literature, although this problem is critical in the testing of small samples. For example, for cylindrical samples, the radius of sample core equals one eighth the sample's diameter. Therefore, for a sample with a 20-mm diameter, 1-mm error in setting the sample in the axis of the testing machine will cause local stress deviation 40% higher than the average stress and result in visibly diminishing the sample's strength by the same amount, practically undermining the point of research.

DNW system was constructed with these contingencies taken into consideration. The investigation is here connected with fixed technology of casting and curing of samples that assure replicability of maturing and loading conditions. Solutions to particular problems are presented in the following.

FIG. 1.
General view of the DNW system for investigation of strength development dynamic.

DNW System

A system for investigation of strength development dynamic, the DNW system (Fig. 1), consists of:

A. Hardware—DNW apparatus, personal computer (minimum 386 processor) to control the test, and the forms for sample casting
B. Software
C. Research technology—as a formal testing procedure

The DNW apparatus itself consists of five main assemblies—press, main drive, sample store, sample conveyor, and positioner—mounted on the supporting structure. The system tests a set of samples by applying uniaxial kinematic pressure without the operator's interference, automatically taking samples from storage in a predetermined sequence, performing the pressure test, and recording the results in the programmed time frame.

Sample preparation precedes testing. The samples are cast in special forms (Fig. 2) made with great accuracy (tolerance $\pm$ 5 μm). A ground steel washer 2 mm thick is put on the bottom of each nest before casting. A similar washer, leveled with the upper edge of the form, is put on top of each sample after casting. In practice, it ensures sample height accuracy of about 0.1 mm and uniform load distribution during the test. Because of the washer, the

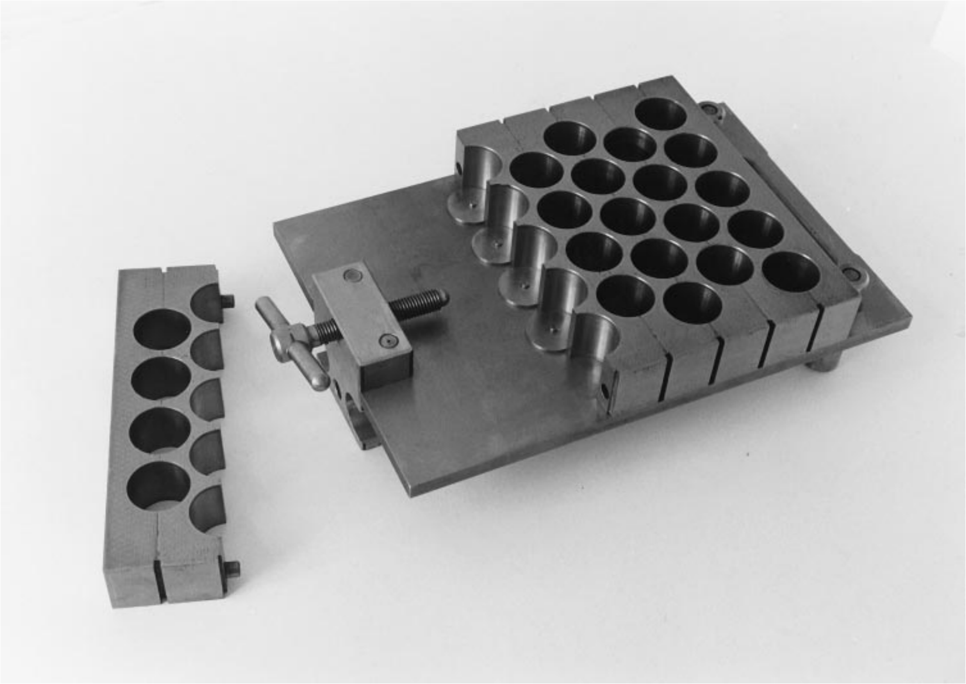

FIG. 2.
DNW system. Form for the casting of samples.

sample can be removed and transported immediately after casting, if it does not become deformed under its own weight.

The samples are put in the apparatus rotating storage. The storage includes an exchangeable carrier disk. It is possible to use the disk for samples with diameters of 20 mm (storage capacity = 60 samples), 30 mm (storage capacity = 40 samples), and 50 mm (storage capacity = 20 samples).

Before the test begins, it is necessary to program all its parameters, including the following:

1. Commentary on the test, which is automatically added to results
2. Sample's "time of birth"—time the samples are prepared
3. Total number of samples divided into groups: maximum number of samples—60; maximum number of groups—10; maximum number of samples in a group—10
4. Time of testing each group's first sample
5. Frequency of testing (may be different for each group)
6. Loading rate during the test
7. Frequency of force readings: maximum 10 readings per second
8. Minimal force, above which the recording of results begins
9. Criterion of the test's completion (maximum force, displacement)
10. Result recording method

Once the programming of parameters is complete, choose the program's "START" option. From that moment on, the test is carried out automatically.

After the computer's clock and the programmed test sequence time overlap, the computer starts running the sequence of test functions. The storage disk makes a partial turn and places the designated sample on the conveyor designed to transport it to the research station. At this moment, the positioner's arm with two sample-centering fingers equipped with electrical contacts is lowered onto the conveyor belt; the conveyor's drive is on until the washer placed on the bottom of the sample short-circuits the positioner's contacts. The 0.05-mm accuracy of centering ensures that the eccentricity error does not exceed 2%, even for samples with 20-mm diameter.

The positioner signals the end of positioning (the sample is set in press axis) and switches off the conveyor drive, thereby activating the press drive. The press piston moves at high speed until the foot of the piston moves within 0.1 mm of the top sample washer. At that point, the program adjusts the speed to the preprogrammed test speed. Force and piston displacement measurements begin, and the results are recorded on the hard disk of the computer. The test continues until the preprogrammed criterion of completion is fulfilled (in terms of force or displacement) or the signal from the marginal displacement gauge is observed. When that point is reached, the press and positioner move back to the starting position. Crushed samples are removed by the conveyor. The system is ready for the next signal from the computer to begin a new measuring cycle.

It needs to be emphasized that the method of sample positioning used in the test ensures accuracy regardless of the sample's surface and the possibility of size-altering shrinkage. The sample is positioned so that its axis, defined during casting by the geometrical axis of the sample's form nest, aligned with the press axis. Actually, the positioning operation takes as its point of reference not the sample itself, but the precision steel washer on the bottom of the cast form.

Accuracy of distance identification between the piston base and the upper washer is 0.05 mm. Such accuracy would be impossible to achieve without the washer, because of irregularities in the sample's surface. Another function fulfilled by the upper washer also becomes apparent—during casting, the washers act as forms. The sample's top surface automatically becomes smooth and flat; consequently, during the compression test, the stresses are distributed evenly throughout the sample's surface.

A prototype of this testing system was created in 1992 (19). The present system differs from the prototype. There is a new computerized control system, a broad range of measurements, and a new force measurement channel. Instead of the previously used strain gauge bridge, a new, original measurement system was constructed at the Building Research Institute. Its main elements are a strain gauge dynamometer (with Vishay gauges) and an 18-bit analogue-to-digital transducer (with Maxim's chip). At present, force measurement range is 100 kN, with 1-N accuracy.

Research Conducted

Many types of materials (mortars, cement pastes, and fly ashes) were tested using the DNW system in 1993 and 1994. The effect of various technologies and chemical admixtures on these materials was tested with particular attention. It was through these tests that the effects

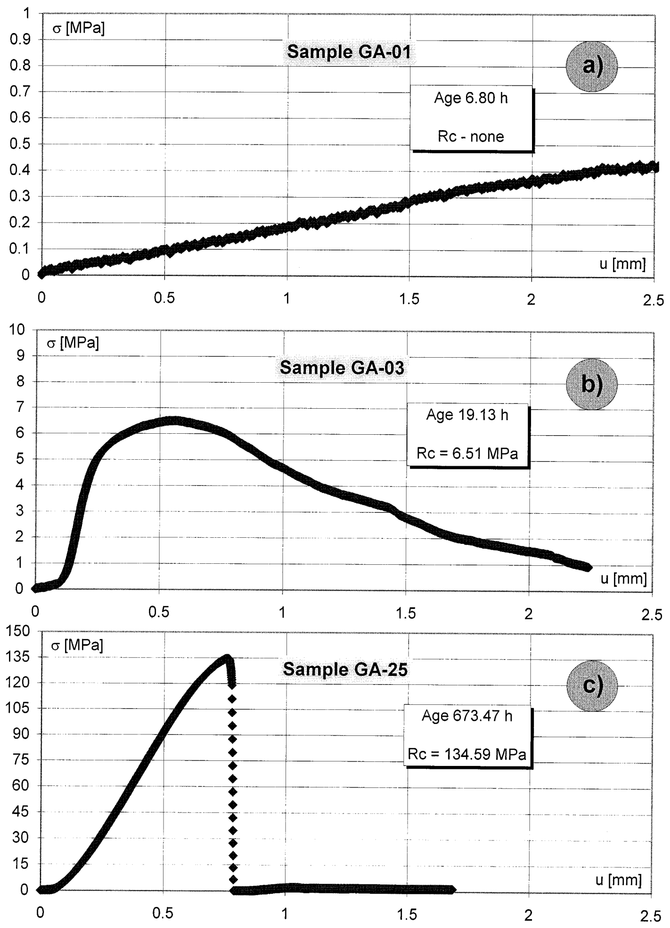

FIG. 3.
Evolution of σ–ε characteristic. (*a*) Before the end of setting—liquid form (no strength); (*b*) soon after the end of setting—intensive softening; (*c*) 4 weeks after casting—absolute brittleness.

of w/c ratio (20) and various superplasticizers (21) on strength development of cement pastes were determined.

One of the main tasks of material engineering of concrete is to control the rate of cement maturation. This rate may be controlled by the application of chemical admixtures, which accelerate or delay the process of cement hydration. Calcium chloride (the most common application) was used in research as an accelerator. As an example of a retarder, calcium gluconate was chosen. The effect of chosen admixtures was tested on cement pastes obtained from Portland cement Chełm 35 at w/c = 0.25. Four different cement pastes were tested with the following admixtures:

1. CA series: admixtures of calcium chloride, 1% of the total cement mass

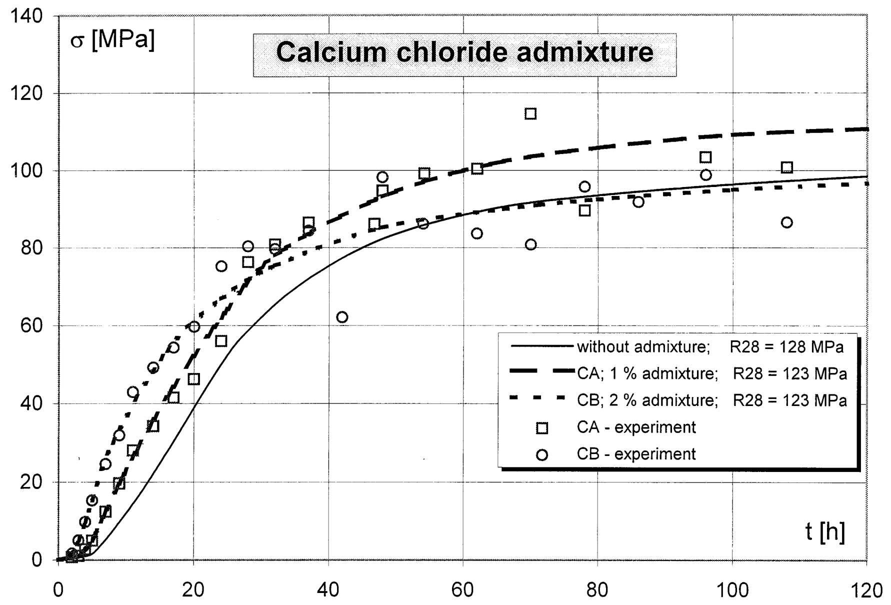

FIG. 4.
Influence of calcium chloride admixtures on strength development.

2. CB series: admixtures of calcium chloride, 2% of the total cement mass
3. GA series: admixtures of calcium gluconate, 0.1% of the total cement mass
4. GA series: admixtures of calcium gluconate, 0.2% of cement mass

For each series, 27 samples, 30 mm in diameter and 30 mm in height, were taken.

Results

Figure 3 shows the evolution of σ–ε characteristics. Shortening of the sample is marked on the abscissa. For a sample 30 mm high, 1.5-mm shortening represents 5% strain. One can see that the 6.8-h-old GA series material is still in a liquid form and does not have any strength (pre-Vicat setting stage); at the age of 19.1 h, one observes intensive softening and complete lack of brittleness; and at the age of 673 h, the phenomenon of softening disappears—the material becomes absolutely brittle. Figures 4 and 5 show the strength development of tested materials.

The departure of strength from the approximating curve and large dispersion of results appear along with brittleness. The results of testing materials without brittle properties lead to a medium deviation of <1 MPa.

Conclusions

Conducted tests indicate that the DNW system may have multiple applications in research of materials. The system can be used to design new materials and to verify the properties of

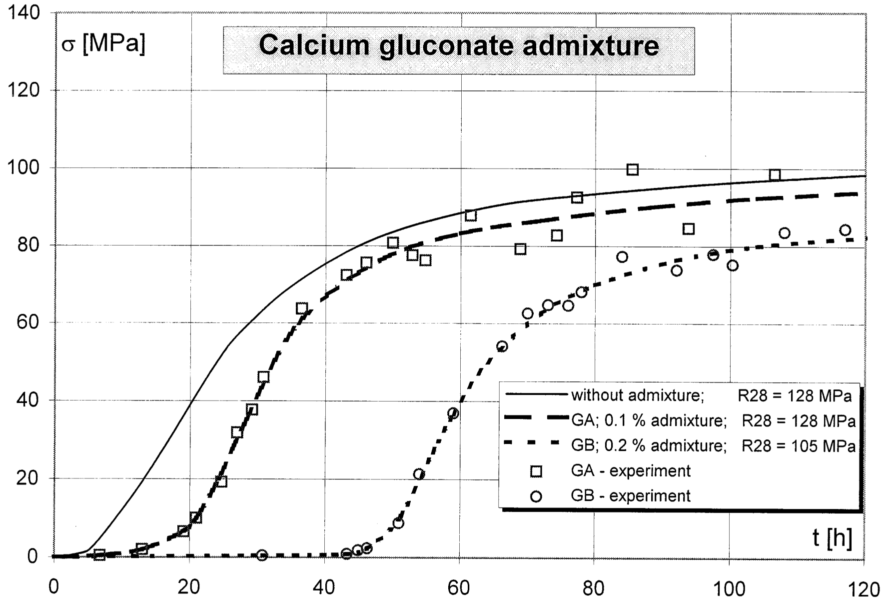

FIG. 5.
Influence of calcium gluconate admixtures on strength development.

building materials already in use. It should be emphasized that the system ensures objectivity of research results, and the research technology developed allows for the conduction of tests regardless of the age of the researched material, as long as the samples do not become deformed under their own weight.

Research conducted thus far contributed to clarifying a series of phenomena, such as the appearance of strength, relationship between the beginning and end of material setting by Vicat, connection between the limit strain and maturity degree, etc. Above all, however, the research demonstrated that the contemporary technology of concrete hardly utilizes the strength properties of cement pastes as a binding material. It should be pointed out that the strength of the samples obtained from cement of 35 mark reached 140 MPa.

The research shows that a large dispersion of strength measurements is caused by the brittleness of material. It is clear that material with such properties is highly sensitive to any local shock or damage. If any damage occurs, a crack inside the sample causes ever increasing stress concentration at its top. In the absence of a mechanism inhibiting crack growth, the destruction of the cracked sample is instant. It explains the main reason for result scatter. Let us point out that the behavior of mortar is completely different—it shows distinct softening.

The research also points to new problems, which should be examined if designing and manufacturing of concrete are to be treated according to contemporary material engineering requirements. The origin of brittle effects is rather unclear, as is the reason for a departure from monotonic strength increase. Periodic declines in strength usually are concealed by researchers who believe that they result from errors. However, the results obtained show that the reason for the declines is objective and comes from the inner transformation of cement paste. To take full advantage of cement binding possibilities, both of these phenomena should be examined, as should the adhesiveness of binding to gravel.

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