Instrumented dynamic tests of building materials

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Abstract. In some specific cases, the building structures can be exposed to extreme dynamic loads. Namely, it can be a car crash, earthquake or the effect of explosion. For these cases, it is useful to know the dynamic mechanical properties of building materials. The paper presents two unique procedures for instrumented impact testing of building materials (concrete and sandstone). These tests may help in practice with selection of suitable materials for buildings and structures which may be threatened by dynamic effects of mechanical stresses. The method how to achieve a higher dynamic material stability is also presented.

1. Introduction

Besides the development of new progressive building materials and technologies aiming at improving physical properties of currently used materials it is also necessary to develop some experimental testing methods for characterization of further partial mechanical properties. Proper mechanical characterization leads to better understanding of material potentialities and enables application of building materials appropriately to particular structures. Regarding the mechanical properties characterizing the behaviour of materials under mechanical loading there are mainly considered static properties, fracture mechanical properties, fatigue characteristics and properties relating to dynamic loads [1, 2]. Currently, the dynamic properties of building materials are tested via various drop tests, split Hopkinson tests, Charpy tests, etc. The problem is that standardization of these tests for building materials is rather low and thus is lower also the global comparability of results [3] and [1].

Dynamic loading of building structures can happen in many cases. Mostly, they are extreme states which should be considered in the stage of design of a building structure according to its utilization and location. This involves buildings situated at seismically active regions where, upon strong earthquakes, vibrations of acceleration of up to 1100 cm/s² (it means around 1 g) can be experienced [4]. Another dynamic loading of a structure can be caused by an explosion (terrorism, industrial premises), e.g. the shock wave created by detonation of TNT has the velocity of 6,900 m/s [5]. Another frequent case of dynamic impact on structures is car crash. Better understanding of the behaviour of materials under dynamic load can thus help in design of structures, in particular the structures with enhanced dynamic impact resistance.

The authors of this paper have aimed at the verification of the functionality of two procedures of dynamic instrumented tests. The former dynamic test comes from the modification of the ISO [6] test which is used in particular for impact tensile tests of polymers. For this test, Charpy impact tester WPM with the capacity 300 J was modernized and modified including its instrumentation to enable impact tensile testing of reinforced concretes. The latter dynamic test was accomplished by means of a modern instrumented Charpy impact tester Instron Ceast 9050, namely in the mode of three-point bending.
impact using specimens from sandstone. Consolidated specimens as well as non-consolidated notched specimens were used. The test was motivated by the standards [7–10] which are used for plastics and metals. There is no relevant standard yet in the field of testing building materials which would specify the procedure of this test and define the size of specimens, for example for concrete, natural stone, etc. The lack of a standardized method for Charpy testing of cementitious composites has led to a great deal of variation in execution between authors.

2. Dynamic tensile test

2.1. Materials and preparation of specimens

Fine-aggregate high-performance concrete was selected for pilot dynamic tensile tests as a standard. This type of concrete is compatible with both fibres selected; owing to the limited grain size and excellent workability of the material due to additives, good dispersion of the fibres can be achieved. Fine SiO$_2$ sand with 0–1 mm grain, CEM 52.5R cement and water were the main components of the concrete mix. Glenium422 super-plasticizer (produced by BASF) was added to achieve good workability with a low water/binder ratio. Elkem 940U silica fume (also produced by BASF), with a typical particle size of 100–500 nm, was used to create an optimized particle packing density, and also for its pozzolanic properties. The mix proportions of the concrete are described in Table 1. Two different types of fibre reinforcement were selected to create specimens with different tensile strength to verify easily the validity of results of the test method. During the pilot testing, only two samples were used per one fiber type. A statistically relevant sets of samples are now being prepared in modified moulds.

| Designation | CEM52.5 R [kg·m$^{-3}$] | Fine aggregate [kg·m$^{-3}$] | Silica fume [kg·m$^{-3}$] | plasticizer | Fibre content [Vol. %] | Fibre material | Length/diameter of the fibre (mm/µm) |
|-------------|--------------------------|-----------------------------|--------------------------|-------------|------------------------|---------------|-----------------------------------|
| A           | 955                      | 1050                        | 115                      | 15          | 0.5                    | Aramid        | 6.0/12                            |
| S           | 955                      | 1050                        | 115                      | 15          | 0.7                    | Steel         | 6.0/150                           |

Steel moulds with polymeric inserts were used to cast the specimens. The mixing procedure was as follows: first, the dry components (cement, sand and microsilica) were mixed together using a concrete mixer, and then the required quantity of water with plasticizer was added and mixed for 3 min. The fibres were incorporated at the end of the mixing process and were mixed for another 60 seconds to achieve good dispersion without any visible agglomerations. The mixes were placed in moulds treated with releasing agent and a vibration table was employed for better compaction of the mixture. The test specimens were demoulded after 24 h and cured for 28 days in water-filled curing ponds.

2.2. Testing procedure and results

Modernization of the Charpy impact tester WPM with the capacity 300 J, including its instrumentation, consisted of the design of appropriate fixtures for clamping a specimen for tensile tests. For instrumentation the fixed chucked head was complemented by a suitable strain gauge transducer. The transducer is based on the shear principle and is used for force recording in the impact process. It consists of the full bridge 4 × 350 Ω and its force range is limited by 80 kN. The sensitivity of the signal 1 mV/V corresponds to loading by horizontal force of 34.8 kN. This specific strain gauge bridge was further connected to the direct current strain gauge amplifier and the whole process of the impact test was monitored in – time by means of a digital oscilloscope connected to PC with a measuring software. The principle of the impact tensile test consists in translating kinetic energy of the impact tester hammer to the tensile specimen through the yoke. The yoke is freely set on the specimen and after the impact of the hammer it acts by tension on the specimen by means of its geometric configuration. The yoke is in a direct contact with the inside surface of one of the two heads of the specimen. The energy consumed for pushing-off the mass of the very yoke is subtracted from the result. After the specimen is broken
the yoke and a part of the specimen are repulsed to the direction of the movement of the hammer. For a better understanding, a scheme of the test and a set of photos from experiments are presented in figure 1. The principle is also described in the standard [6]. The impact speed of the Charpy hammer was 5.6 m/s with total impact energy capacity 7.5 J.

![Test in tensile impact-strength mode.](image1)

**Figure 1.** Test in tensile impact-strength mode.

![Tensile impact specimen.](image2)

**Figure 2.** Tensile impact specimen.

The real shape of the tensile specimen is shown in figure 2. The results of the tests are (i) magnitudes of the energy needed for breaking specimens and (ii) records of the force – time dependence upon impact tension. All results are presented in table 2 and figure 3. Table 2 also summarizes the tensile peak forces recorded within the impact process.
Table 2. Results – Impact-strength test.

| Designation | Fibre material | Total fracture energy [J] | Peak force Fmax [kN] |
|-------------|----------------|---------------------------|----------------------|
| S2B_1       | Steel          | 120                       | 76.1                 |
| S2B_2       | Steel          | 90                        | 75.2                 |
| A_1         | Aramid         | 51                        | 73.4                 |
| A_2         | Aramid         | 57                        | 73.4                 |

Figure 3. Comparison of dependences „Force – Time“ during dynamic tensile impact-strength tests.

It can be seen from the results of pilot tests that the test procedure is functional, however the shape of test specimens is not ideal. Due to a high sensitivity of concrete to stress concentration at notches the failure of specimens with aramid fibres took place at the transition from the grip holder to the measuring length. This problem did not occur when testing specimens with steel fibres. These specimens always failed at the beginning of the measuring length. Differences in fractures as well as the fracture surfaces are seen in figure 4.

Based on the experience obtained, the modification of the shape parameters of the test specimens will be performed. According to the nature of material and used test method, as an ideal shape a tensile type specimen with a zero-gauge length was selected. Further systematic research will continue with such prepared specimens.

Although the specimens with aramid fibres fractured in the locations with a significantly larger load-bearing cross section than that of specimens with steel fibres, it was found that their tensile resistance was lower than that for specimens with steel fibres. Both maximum tensile forces attained and energy consumed for dynamic tensile fracture of a specimen were lower in case of specimens reinforced with aramid fibres, thus the results of both obtained records are consistent. To be specific, the maximum average force for specimens with steel fibres was found to be higher by 2.3 kN and the consumed energy to be higher by 51 J on average. A zero equidistance of curves representing the „force – time“ dependence at their ascending part is worthy of remark. This attests to equal dynamic E modulus for both compositions of materials. This is caused more likely by the same composition of the concrete matrix and its volume as compared to the volume of fibres, especially in the case of aramid fibres.
The problem of the effect of volumetric part of fibres on the development of E modulus was dealt with by e.g. [13].

Figure 4. Left side: Specimens with aramid fibres and fracture surface, Right side: Specimens with steel fibres and fracture surface.

3. Instrumented Charpy test for sandstone

3.1. Materials and preparation of specimens
The stone used for testing was the arkose sandstone, quarried in Božanov (CR). The material can be characterized as a quasi-brittle inelastic silicate composite [11]. Test specimens were cut from the sandstone semi-product with dimensions of 10 mm × 10 mm × 88 mm. An initiation notch 1 mm thick and 1.5 mm deep was made on one side of each specimen in the middle of the specimen length. The initiation notches were situated identically in the direction of sedimentation. The real shape of the Charpy specimen is shown in figure 5.

Figure 5. Charpy specimen.

The dynamic tests were accomplished by means of a modern instrumented Charpy impact tester Instron Ceast 9050 in the mode of three-point bending impact. Consolidated specimens as well as non-consolidated notched specimens were used. Stone specimens were treated by the stone strengthener, REMMERS KSE 300 E, with a silicic acid ester base. This product contained a special elasticised component and the possible effect of the component on strengthening sandstone was evaluated. The expected SiO₂ gel deposition rate for REMMERS KSE 300 E was around 30 w%. According to
the producer information [12], the ‘elasticised’ stone strengthener could perform better in the case of stones with large pores or stones containing micro-cracks. The treatment of stone specimens with the liquid strengthening products was performed by placing the specimens in a dish, followed by gradual pouring the liquid up to 5 mm above the height of the liquid level (which represented the half of the specimen height). After the time period of two hours, the impregnated stone specimens were removed from the liquid product, the wet surface was shortly whipped using a paper and then the specimens were weighted to monitor the amount of the liquid soaked by stone. Before mechanical testing, all specimens were stored for 4 weeks at 20°C and 60% RH and during this time the chemical reaction responsible for the SiO$_2$ gel formation in stone pores occurred and the organic part of the product released. The weight gains after the four weeks of the storage were recorded for all specimens and the total weight increase in relation to the treatment was calculated. The obtained data are presented in Table 3. The measured product gel amount in the treated stone specimens (four weeks after the treatment) was 31.5 w% for the REMMERS KSE 300 E. This finding was in a good conformity with the technical data provided by manufacturer.

3.2. Testing procedure and results

The test was motivated by the standards [7–10] which are used for plastics and metals. The test procedure is very similar to tensile impact test, with following differences: a specimen is loaded in the mode of three point bending impact, loading sensor is placed into the active part of the hammer and the shape of the hammer is modified. The impact speed of the Charpy hammer was 3.8 m/s with total impact energy capacity 7.5 J. The set of photos from experiments can be seen in figure 6. The span of supports was 60 mm [10].

![Figure 6. Charpy three-point bending test – Instron Ceast 9050.](image)

The results of the tests are (i) magnitudes of the energy needed for breaking specimens in three-point bending loading mode and (ii) records of the force – time dependence upon impact mode in three-point bending. All results are presented in table 3 and figure 7. Peak forces achieved during the impact process were evaluated and summarized in table 3. During the pilot testing, seven samples were used per one group of the sandstone.

The results show clearly positive effect of consolidation by the strengthener REMMERS KSE 300 E from the viewpoint of sandstone dynamic mechanical properties. After consolidation of specimens the average energy, consumed for breaking a specimen, was increased by almost 20%. Considering the natural origin of the material tested the scatter of the results was not distinctive and the results obtained can be qualified as representative. From the viewpoint of force peaks attained at the tests it can be stated that due to the consolidation their average magnitude was increased by 62% as compared to non-consolidated material. However, the scatter of force peaks was somewhat greater. A higher scatter of resulting magnitudes is caused most probably by a lower geometric homogeneity of sandstone grains in the location of fracture which is characteristic for this type of natural materials [14] and [15]. As can be seen in figure 7 there is also some difference in the shape of “force-time” curves. After consolidation
the dynamic E modulus of sandstone became higher and thus the material after consolidation became stiffer. The instrumented Charpy tests for this type of material appear to be functional, but however, until now no standard was defined which would clearly specify this procedure (specimen size, the way of performance, etc.). The testing method can also form an appropriate supplement to other dynamic test methods as it is shown e.g. in [16].

Table 3. Results – Charpy test.

| Specimen no. | Total energy [J] | Peak force [N] | Mass gain by treatment [w%] | Product gel deposition rate [w%] | Description               | Comment       |
|--------------|-----------------|----------------|-----------------------------|---------------------------------|---------------------------|---------------|
| 1            | 0.109           | 729.7          | -                           | -                               | notched without cons.    |               |
| 2            | 0.112           | 1173.5         | -                           | -                               | notched without cons.    |               |
| 3            | 0.115           | 938.7          | -                           | -                               | notched without cons.    |               |
| 4            | 0.111           | 991.9          | -                           | -                               | notched without cons.    |               |
| 5            | 0.115           | 1037.4         | -                           | -                               | notched without cons.    |               |
| 6            | 0.111           | 631            | -                           | -                               | notched without cons.    |               |
| 7            | 0.109           | 658            | -                           | -                               | notched without cons.    |               |
|              | Mean            | 0.112          | 880.0                       | -                               |                           |               |
|              | Stand. deviation| 0.0023         | 193.0                       | -                               |                           |               |
| 8            | 0.135           | 1560.8         | 2.03                        | 35                              | notched consolidated     | KSE 300E      |
| 9            | 0.123           | 1016.8         | 1.73                        | 32                              | notched consolidated     | KSE 300E      |
| 10           | 0.128           | 1257.2         | 1.77                        | 33                              | notched consolidated     | KSE 300E      |
| 11           | 0.136           | 1535.2         | 1.91                        | 34                              | notched consolidated     | KSE 300E      |
| 12           | 0.14            | 1707.1         | 1.51                        | 30                              | notched consolidated     | KSE 300E      |
| 13           | 0.132           | 1147.3         | 1.44                        | 30                              | notched consolidated     | KSE 300E      |
| 14           | 0.145           | 1767.4         | 1.48                        | 32                              | notched consolidated     | KSE 300E      |
| Mean         | 0.134           | 1427.4         | 1.696                       | 32.286                          |                           |               |
| Stand. deviation | 0.0068   | 267.1          | 0.2107                      | 1.7496                          |                           |               |
Figure 7. Examples of „Force – Time“ dependences during Charpy test with or without consolidation.

Further experimental research on the effect of consolidation on dynamic resistance of sandstone material will be performed. Further tests of unnotched specimens as well as notched specimens with a different shape of the notch will be carried out as well.

4. Conclusions
Two procedures for impact testing of building materials were introduced, including the pilot tests results. The feasibility and usefulness of the procedures for characterization of the sandstone and concrete samples was assessed. The influence of consolidator REMMERS KSE 300 E on the impact resistance of the sandstone specimens was also evaluated. The following conclusions can be drawn:

– Results of the dynamic tensile strength tests showed feasibility and usefulness of the proposed test method for description of the mechanical properties of the cement-based materials under impact load. Tested specimens with lower tensile strength under static load showed lower characteristics under impact load as well. The method also showed consistent results in terms of coherency of achieved total fracture energy and peak force.

– Adjustments in the shape parameters of the test specimens are required due to a higher sensitivity of concrete to stress concentration in the notches. Specimens with a zero-gauge length were proposed for further testing, as they seem to be more suitable for designed test configuration.

– Regarding the Charpy test of sandstone, the test method was evaluated as suitable to assess the dynamic resistance of quasi-brittle inelastic silicate composite materials.

– The positive influence of consolidator REMMERS KSE 300 E on the impact resistance of the sandstone was proven; the average consumed energy, needed to break a specimen, was found to be increased by almost 20% for consolidated specimens. Also, due to the consolidation process the average force peak was increased to 1427.4 N, i.e. by 62%, as compared to non-consolidated material.

Although used testing methods are not standardized for the quasi-fragile materials, their application for a further characterization of materials can be recommended.

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