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Dynamic behaviour of "Collapsible" concrete

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Abstract. In this work a particular cement composite material for protection of structures and infrastructures against accidental actions, such as blast or impact, has been investigated. An experimental procedure has been developed in order to assess static and dynamic behaviour of energy absorbing cementitious composites. The granular cementitious composite has been studied focusing attention to compressive strength, high deformation and energy dissipation capacity which are important characteristics for an absorber material. An experimental characterization of the material behaviour under compressive static and dynamic loadings has been carried out. Different deformation velocities have been studied in order to define the material behaviour in a wide range of strain rates. The velocity range up to 0.1 m/s is investigated by means of a universal servo-hydraulic MTS 50 kN testing machine. Some preliminary results have been reported and discussed in the present work.

1. Introduction

One of the major concerns of our society focuses on the development of strategies to provide structures and infrastructures, especially if they are critical, with adequate measures of either active or passive protection against accidental actions, such as impact and blast. During the last years, researchers developed several high performance materials in order to increase the blast resistance performance of structures, focusing their attention mainly on strength, stiffness and resilience. For example the use of High Performance Fiber Reinforced Cementitious Composites (HPFRCCs) has been intensively studied for repairing, retrofitting, upgrading and/or protecting existing structures. This category of materials is able to sustain large amount of strain with not negligible stress. Furthermore, it has been recently shown ([1,2]) that HPFRCCs are able to retain a significant level of their original performance, even when exposed to conditions such as high temperature and high strain rates. However, as the American Concrete Institute underlines, a high-performance concrete is a "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices" [3].

Starting from this observation, the search of a different class of materials, meeting the needs and performance requirements for such special conditions, has been initiated. O'Neil et al. [4] have developed a concrete called "frangible concrete", due to its property of breaking into small fragments, which are less harmful as well as easily lost in the environment. The material is thus able to absorb and dissipate, through the diffused fracture process, a high amount of energy. A similar concept has been developed by Caverzan and Ferrara [5] in tailoring a "collapsible concrete". This material has shown merits in dissipating a significant amount of the energy input generated by either a far or a near field explosion and thus prevent it from being transferred to critical load bearing elements. A possible application of the "collapsible concrete" for protection could be found in protective sacrificial screeds. The use of protective screeds for reinforced concrete structural elements has already been investigated, metallic foams have been especially used in such studies [6–9]. However, real applications on existing or new structures have never developed due to their high cost. The key idea highlighted by Ferrara et al. [10,11] is to have a cementitious composite featuring a significant energy dissipation at a quite low strength level and low cost.

The relevant deformation capacity is mainly dependent on a rearrangement of the aggregate granular skeleton obtained after the failure of weak inter-granular bonds. Three peculiar concepts have been applied: the use of cement paste characterised by a low strength and a not negligible fracture toughness (obtained also by using air entraining admixture AEA); an aggregate granular skeleton with a grain size distribution as narrow as possible which can lead to a high capacity of the material to undergo significant deformation and finally a low dosage of cement paste in order to assure just a minimum inter-granular bonding without filling the voids between the aggregate.

In order to study in depth the potentiality of "collapsible concrete", by investigating in particular its dynamic behaviour at different strain rates, an extended experimental campaign has been planned. In the present work preliminary results have been reported and some strategies are highlighted in order to improve the material performance.

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Table 1. Mix Design.

Constituent	dosage
Cement type I 32.5	195.12 kg/m^3
LWA	376.02 kg/m^3
Water	117.12 l/m^3
AEA	2.34 l/m^3

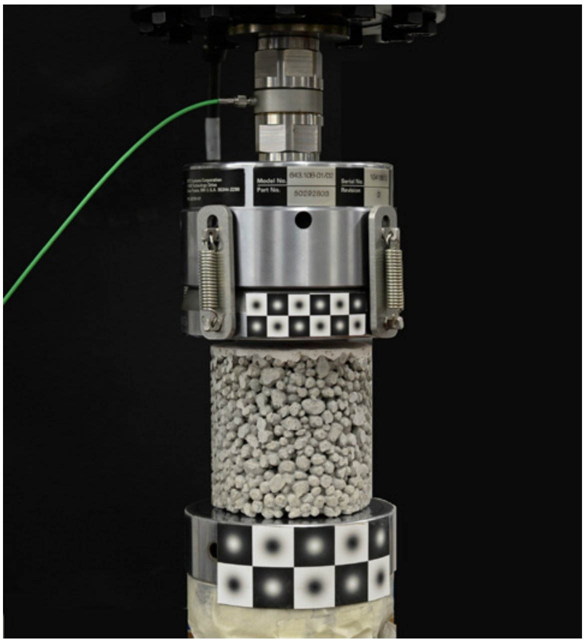
2. Material and experimental test description

The "collapsible" concrete studied in the present work has been cast following the mix design reported in Table 1. The material obtained is characterised by a water-cement ratio (w/c) equal to 0.6 and a percentage of mortar in volume equal to around 26% which correspond to the minimum theoretical void ratio of a densely packed mono-size arrangement of spheres. Expanded clay Light Weight Aggregate (LWA) with a nominal grain size range equal to 3–8 mm was chosen as aggregates. Sixteen cylindrical samples of diameter and length equal to 80 mm have been cast. Differently from what it was done previously by Ferrara et al. [10, 11] the ratio between diameter and length (d/l) has been limited to 1 in order to reduce the influence of friction even if this contribution is important when practical applications on real structural elements are considered.

An experimental program has been carried out to properly identify the mechanical properties of "collapsible" concrete under static and dynamic conditions. Uniaxial compression tests on the cylindrical samples have been performed by means of a universal servo-hydraulic MTS testing machine (Fig. 1a) in the European Laboratory for Structural Assessment (ELSA). The machine has a maximum load capacity of 50 kN and it can impose a maximum displacement rate equal to 300 mm/s. A Kistler 9341 piezoelectric load cell with a maximum capacity of 30 kN has been installed in order to improve the quality of the signal recorded during the tests (Fig. 1b).

Signals have been acquired by employing a National Instrument PXIe-6366 Simultaneous Data Acquisition recorder with a maximum sampling-rate of 2 MHz. In addition a high-speed camera IDT-Y4 has been intensively used. It is able to perform at 4000 fps with maximum resolution, however the acquired frame-rate can be increased to 200 000 fps by reducing substantially one dimension of the recorded image.

(a)



(b)

Figure 1. Test set-up: press device and high-speed camera (a); detail of the sample, piezoelectric loading-cell and optical targets (b).

3. Test results and discussion

Uniaxial compression tests have been performed in order to investigate the influence of strain rate on the material behaviour. Four different displacement rates have been applied (0.1, 1, 10, 100 mm/s) and some reference quasi-static tests have been performed exploiting the same test set-up configuration. The results of compressive tests are shown in Figs. 2–6 in terms of nominal longitudinal stress (σ_v) versus longitudinal strain (ε_v). The behaviour exhibited is different from what has been reported by Ferrara et al. [11], the stress plateau observed after the initial linear elastic range has not been clearly identified in this series of tests, only few samples have shown a limited plateau up to 0.05 strain. It is thought that the main reason for that should be searched in the different specimen geometry and test set-up. In fact, previous experimental campaigns have been conducted on cylindrical samples of diameter equal to 200 mm and length equal to 50 mm, and consequently the test set-up was characterized by particular boundary conditions that accentuate the contribution of friction. The boundary conditions and sample geometries selected by Ferrara

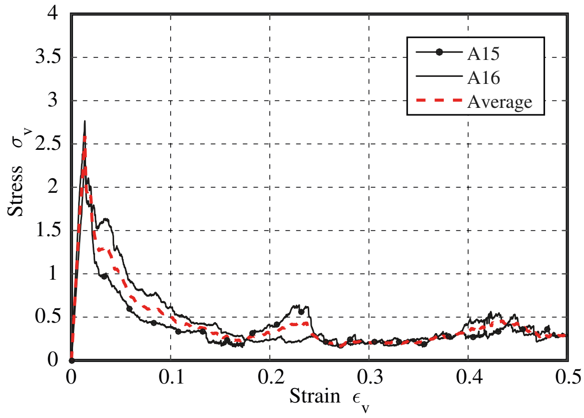


Figure 2. Stress vs. strain curves for the static tests.

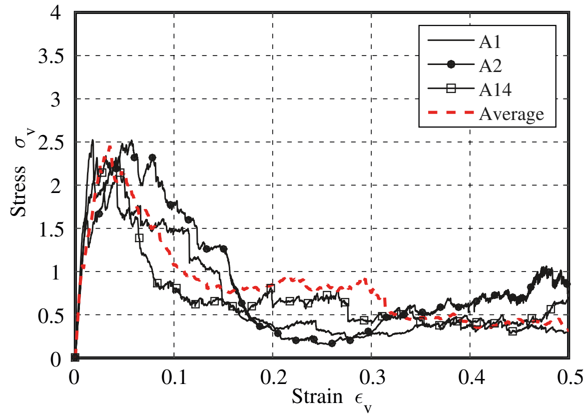


Figure 3. Stress vs. strain curves for the dynamic tests with a displacement rate $\dot{\delta}$ equal to 0.1 mm/s.

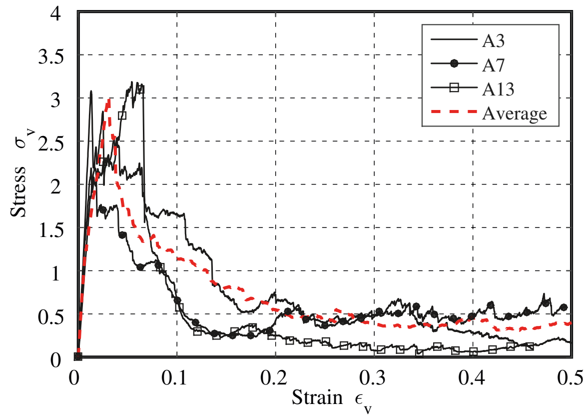


Figure 4. Stress vs. strain curves for the dynamic tests with a displacement rate $\dot{\delta}$ equal to 1 mm/s.

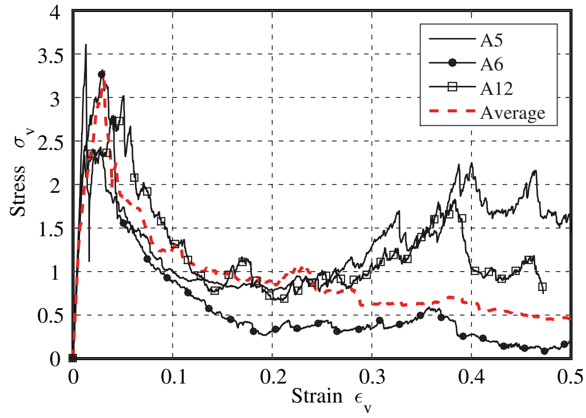


Figure 5. Stress vs. strain curves for the dynamic tests with a displacement rate $\dot{\delta}$ equal to 10 mm/s.

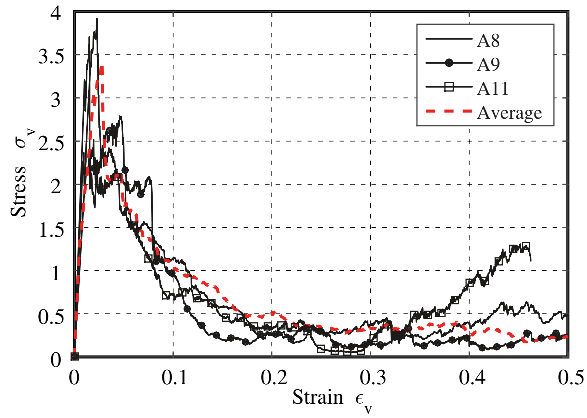


Figure 6. Stress vs. strain curves for the dynamic tests with a displacement rate $\dot{\delta}$ equal to 100 mm/s.

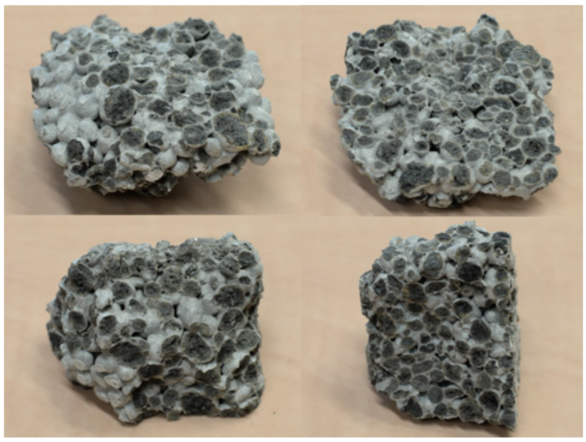


Figure 7. Pieces of failed samples. Intra-granular failure can be clearly observed.

et al. [10] were justified by the needs to focus on some particular engineering application as explained by the authors. Moreover, the decay in the material performance, linked to the reduction of friction contribution, has been emphasised by the higher compressive peak strength obtained in these new experimental tests.

The use of a mortar with w/c ratio relatively low has led to compressive strength of matrix higher than the light weight aggregates strength. As Figs. 2–6 show, when the peak strength is reached a sudden release of elastic energy generates a drop in the stress level associated to aggregate failures (Figs. 7 and 9). The intra-granular failure does not allow to develop a proper

Table 2. Peak strengths and energies absorbed.

Sample code	$\dot{\delta}$ [mm/s]	σ_{Peak} [MPa]	$\sigma_{Peak,av}$ [MPa] (std)	G_{tot} [J/dm^3]	$G_{tot,av}$ [J/dm^3] (std)	G_{10} [J/dm^3]	$G_{10,av}$ [J/dm^3] (std)	G_{20} [J/dm^3]	$G_{20,av}$ [J/dm^3] (std)
A15	0.01	2.77	2.60	245.34	225.69	118.65	100.87	154.76	133.07
A16	0.01	2.44	(0.23)	206.04	(27.80)	83.09	(25.14)	111.38	(30.67)
A1	0.1	2.53	2.46	349.64	393.44	164.50	169.46	247.80	253.37
A2	0.1	2.52	0.11	459.23	(58.01)	192.90	(21.39)	296.50	(40.63)
A14	0.1	2.34		371.44		150.99		215.82	
A3	1	2.84	3.04	391.73	318.82	189.43	171.57	278.88	222.92
A7	1	3.08	(0.18)	310.07	(68.95)	134.25	(32.33)	167.05	(55.92)
A13	1	3.19		254.66		191.05		222.83	
A5	10	3.61	3.31	683.41	534.43	164.64	181.26	251.55	260.59
A6	10	3.32	(0.30)	323.09	(188.08)	175.32	(20.26)	228.37	(37.57)
A12	10	3.02		596.78		203.83		301.86	
A8	100	3.92	3.47	358.82	329.85	185.59	178.09	247.68	227.75
A9	100	2.79	(0.60)	286.23	(38.45)	190.30	(17.23)	224.43	(18.50)
A11	100	3.71		344.49		158.39		211.13	

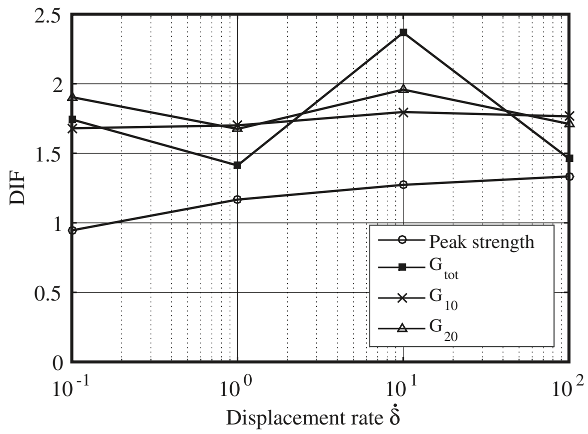


Figure 8. Dynamic increase factor trends for peak strength and energies.

grain redistribution which is the principal resource of energy dissipation. For such reason relative low values of dissipated energy can be observed in Table 2, where peak strength and energies absorbed up to different strain levels (0.1 $\rightarrow$ G_{10}, 0.2 $\rightarrow$ G_{20} and 0.5 $\rightarrow$ G_{tot}) are listed. In order to highlight the influence of strain rate on the material behaviour the Dynamic Increase Factors (DIF), computed as the ratio between dynamic and static material characteristics are listed in Table 3. While the DIF of peak strength shows an increasing linear trend from 1 to around 1.33 for displacement rate equal to 100 mm/s, the DIF trends related to energies are not clearly defined especially when the total energy G is considered. The DIF for the energy G_{10} related to a strain level equal to 0.1 exhibits a stable value close to 1.7. This would imply that in the first part of the fracture process the material is able to absorb 70% more energy in dynamic conditions.

Table 3. Dynamic Increase Factors of peak strength and energies.

$\dot{\delta}$	DIF_{Peak}	DIF_{Gtot}	DIF_{G10}	DIF_{G20}
0.1	0.95	1.74	1.68	1.90
1	1.17	1.41	1.70	1.68
10	1.27	2.37	1.80	1.96
100	1.33	1.46	1.77	1.71

4. Conclusions

The behaviour of "collapsible" concrete when subjected to different displacement rates has been investigated. A preliminary experimental campaign has been carried out by means of uniaxial compression tests. Tests have been carried out by means of a universal servo-hydraulic MTS testing machine, which is able to impose a maximum displacement rate equal to 300 mm/s. From the experimental results presented in this research work some important conclusion can be drawn for the specific concrete mix under consideration:

- the sample geometry and the boundary conditions adopted have limited the influence of the friction, highlighting a different behaviour from that reported in previous studies. However, the friction and its passive confinement effect play an important role when real applications are considered and can not always be neglected;
- the change in material behaviour has been emphasized by the relatively high compressive strength of the matrix with respect to the LWA strength, which has led to an intra-granular failure. This type of rupture has not allowed the development of a proper granular compaction which is the main resource of energy absorption;
- "collapsible" concrete has exhibited a strain rate sensitivity in terms of compressive strength, the DIF

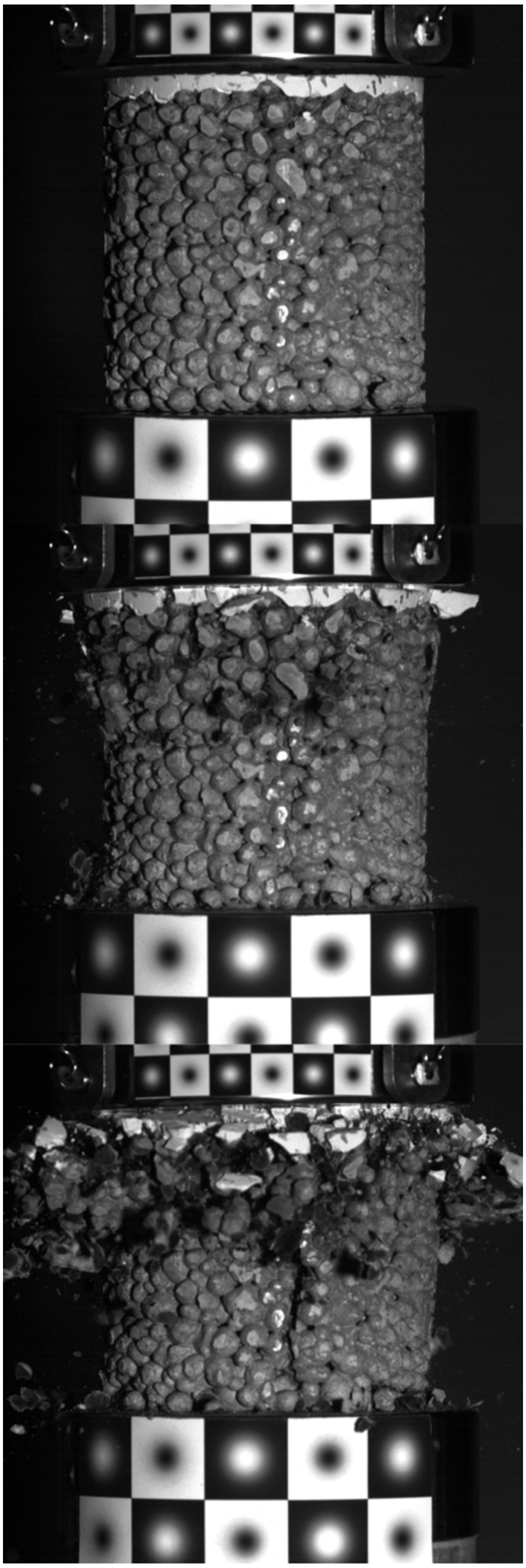


Figure 9. High speed photo sequence.

has increased up to 1.33 when passing from quasi static to dynamic tests at 100 mm/s;

- even if the behaviour underlined is slightly different from previous research in dynamic regime, the energy absorbed in the first stage (up to 0.1 strain) is about 70% higher than what has been recorded in quasi-static tests.

The adopted experimental procedure is going to be used as an efficient method to evaluate similar type of materials; research work is continuing using different aggregates and changing matrix properties in order to improve the material dynamic performance. For instance, it is expected that a combined use of micro-fibres and matrix characterised by a lower compressive strength could improve significantly the material behaviour observed in the tests. The effects of passive confinement due to friction could be replaced by an internal confinement, obtained by introducing an appropriate amount of micro-fibre; this aspect is part of the research work in progress at the ELSA laboratories.

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