Construction and Building Materials 153 (2017) 247–260

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Uniaxial confined compression tests of cementitious materials

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HIGHLIGHTS

- A setup to perform confined compression tests at high pressures has been developed.
- Increase of the sand fraction results in increase of the secant bulk modulus.
- Bulk modulus of reloading branches depends almost linearly on the unloading pressure.
- Cracks perpendicular to the axis were observed in specimens with coarse sand.
- No damage has been identified in fine sand specimens.

ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 21 May 2017
Accepted 2 July 2017

Keywords:
Uniaxial confined compression test
Equation of state
Cementitious composite
Mortar

ABSTRACT

This paper aims at presenting the development of an experimental setup to perform confined compression tests of mortar and cement paste specimens at high pressures. The paper presents the effect of water/cement ratio (w/c) as well as the ratio of fine aggregate (sand) and its maximum grain size on the measured pressure – volumetric strain dependence (equation of state). Decrease of w/c ratio in a cement paste mix results in increase of the secant bulk modulus of the loading branch. The study includes unloading and reloading at different load levels. The bulk modulus of the reloading branch of a given composition depends almost linearly on the pressure magnitude. The secant bulk modulus (loading branch) of mortar specimens increases monotonically with the volumetric sand fraction. The experimental study shows a good repeatability of the different cement paste specimens and of specimens with fine sand; a relatively large scatter of the results is obtained for specimens with coarse sand. The developed damage was identified and recorded at the end of each test. In cement paste specimens cracks were identified only in the case of w/c = 0.50, while in the other specimens, no cracking was observed. In the mortar specimens with coarse sand, perpendicular cracks to the specimen axis were observed, while in the specimens, that contain fine sand, no damage has been indicated.

1. Introduction

The severe loading on a concrete structure either due to high intensity explosions or due to impact and the following penetration of a projectile, may produce very high pressures at the order of hundreds of MPa or even GPa. Therefore, it is extremely important to investigate the behavior of concrete under exceptionally high hydrostatic pressures within the range of hundreds of MPa and up to 1 GPa and even beyond. The behavior of concrete at this extremely high range of pressures is important and essential to support the development of an equation of state (EOS) for concrete as well as for other cementitious composites, however it has not been adequately investigated, and therefore the mechanisms of their deformation and damage that are developed within that range of high pressures is at least partly obscure and far from being clearly understood. This is partly because of the extensive experimental work that is required to investigate the behavior of concrete specimens under such high pressures, while the application of controlled extreme pressures requires special equipment and expensive setups and testing is associated with a wide variety of technical problems.

It is very difficult to produce static pressures of that magnitude and therefore some attempts have been directed towards dynamic testing, that allows obtaining of shock Hugoniot adiabate. The major dynamic techniques are:

1. Using a split Hopkinson pressure bar (SHPB) where the specimen is located within a metallic ring [1,2] or has no confinement [3] (uniaxial [1,3] or confined tri-axial [2,4] dynamic

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.010

Table 1
Chemical composition of Portland cement.

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	K_2O	Na_2O	P_2O_5	Mn_2O_3	SO_3
% by weight	63.03	18.53	5.60	3.43	1.37	0.38	0.45	0.14	0.53	0.04	2.53

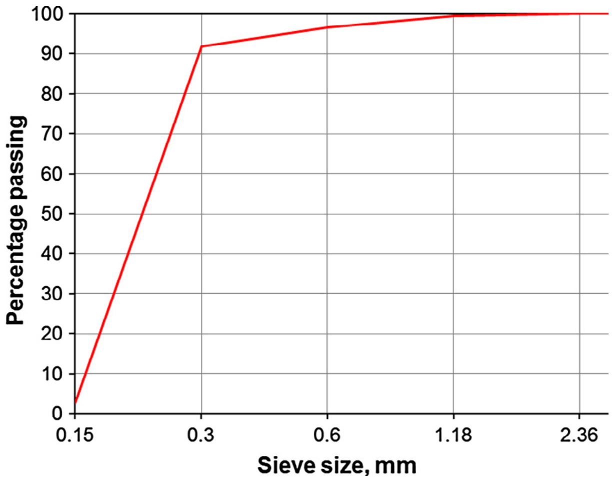

Fig. 1. Grading curve of normal weight fine aggregate.

pressure) for either plain [1–3] and fibrous [5,6] specimens. The specimens in most of these tests are relatively small and therefore tests are focused on mortar [6] or concrete with small aggregates only (grain size 5 mm [1] to 20 mm [3]) specimens as well as with specimens, which are performed from “concrete like” materials [2,7]. However there exist some devices to perform the experiment for larger specimens [8] which were carried out only to investigate failure only.

2. Inverse impact planar test [1,9,10] with specimen impact to a steel backup plate. The specimen in these tests may be either confined or unconfined. They may be larger than in direct SHPB experiments and may contain larger aggregates.

One proposed approach to obtain the EOS for concrete with coarse aggregates and overcome the above experimental limitations is to carry dynamic test on mortar or cement paste specimens and then conduct numerical simulations of a mix on a mesoscale level to incorporate the coarse aggregates effect and in order to obtain the EOS for concrete [11].

Static tests may be conducted on larger specimens containing coarse aggregates as well, however application of three axial pressures of high magnitude is not straightforward and special tailor made hydraulic systems are required. Several studies are reported in the literature on either 3-axial pressure loading [12–16] or a uniaxial confined technique [3,17,18]. The 3-axial loading tests are performed either by extreme high-capacity tailor made hydraulic triaxial press [19,20–22], or with custom made equipment like the MTS material testing system where the specimen is jacketed with a rubber membrane [15] and the confined pressure is applied via a cell with the confining fluid. These expensive tests allow pressures up to ~0.6 GPa for relatively large concrete specimens.

Under uniaxial loading, without any confining pressure, the concrete demonstrates brittle behavior where failure is caused by localized shear damage. Quite to the contrary, at high levels of confining pressures, the concrete behaves like a ductile material, and its failure is associated with diffuse material damage, pore collapse, cracking and de-bonding at the cement paste–aggregate interface. This ductile behavior allows conducting uniaxial strain tests up to high pressure levels under confinement conditions [3,23] in which the specimen undergoes relatively large deformations. Because of the dilatancy of cementitious materials [24,25], such tests cannot be directly used to determine the EOS. However, after calibration of the mixture bulk modulus they may be used for verification of theoretical models [26,27].

In order to simulate analytically or numerically the complicated behavior of concrete under high multi-axial loads, an appropriate concrete model is required. Two major analytical approaches to modeling the concrete bulk behavior under extreme high pressure are presented in the literature. The first approach is based on the macro scale level. The most known equations of state representing this type are the Shock-Hugoniot [1,8,11], Tait -Murnaghan [12,13], and Tillotson EOS [28] for dry materials and the $P \sim \alpha$ [29,30], and Lyakhov [31,32] EOS for multi-phase materials. The second approach to model concrete behavior is a multi-level approach taking into consideration the microstructure of the cementitious materials. The first type utilizes continuum damage theory coupled with a plasticity model [19,33], and the second type uses a discrete element modeling (DEM) concept [34].

In light of the above in the previous studies the authors have developed the first generation of a new multi-scale mix based model for unsaturated cementitious materials that considers the microstructure of cement paste and concrete [26,27].

This paper aims at presenting the development of an experimental setup to perform confined compression tests of mortar and cement past specimens at high pressures up to 300 MPa. The paper presents the effect of water/cement ratio as well as the ratio of fine aggregate (sand) and its maximum grain size on the measured pressure – volumetric strain dependence.

2. Materials and setup

2.1. Mix proportions

Cement pastes with different water to cement (w/c) ratios, and mortar mixes with various sand contents were tested.

The cement was a commercially available ordinary Portland cement of CEM I 52.2N type. The chemical composition of the Portland cement according to (ASTM C114-07, 2007) is given in Table 1. The loss on ignition was 4.12% by weight. The specific surface area of the Portland cement, tested according to (ASTM C114-07, 2007), was 421.7 ± 40 m^2/kg. The density of the tested cement according to (ASTM C188-09, 2009) was 3.150 g/cm^3. Setting times were determined in accordance with (ASTM C191-08, 2008). The initial setting time was 160 min and final setting time was 220 min.

Natural quartz sea sand was used as fine aggregate in the mortars. Sieve analysis was performed using standard sieves, in compliance with the ASTM standard test method for sieve analysis of fine and coarse aggregate (ASTM C136-06,

Table 2
Compositions of the cement past mix per 1 L.

Notation	W/C	Cement, g	Water, g	Degree of hydration	STDV DOH	Porosity
P33	0.33	1544.5	509.7	60.9%	0.48%	0.148
P40	0.40	1393.8	557.5	65.0%	0.46%	0.209
P50	0.50	1223.3	611.7	72.1%	0.14%	0.272