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# High-pressure uniaxial confined compression tests of mortars

D.Z. Yankelevsky, Y.S. Karinski *, S. Zhutovsky, V.R. Feldgun

*National Building Research Institute, Technion – Israel Institute of Technology, Technion City, 32000 Haifa, Israel*

## 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.
- There is negligible size effect for all types of unsaturated mixture compositions.
- The Hirsch mixture model shows a good agreement with the test results for all levels of fine aggregate content in mortars.

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## ABSTRACT

The paper presents the development of an experimental setup to perform confined compression tests of cementitious paste, mortar, and concrete specimens at high pressures up to 1 GPa as well as the validation of the multi-scale model for the equation of state (EOS) of mortars. The test results for the EOS show that the secant bulk modulus of the loading branch monotonically increases with the content of fine aggregate. The comparison of the loading branches of the EOS for unsaturated specimens of two different specimen sizes indicates that there is negligible size effect for all types of the mixture compositions. Validation of the multi-scale model proposed previously for the EOS of a cement paste shows good agreement with the test results at the high-stress range with slight deviation at the lower stresses. It was demonstrated on mortars with a water to cement ratio of 0.50 that the Hirsch mixture model shows a good agreement with the test results for all levels of fine aggregate content in mortars.



## 1. Introduction

Investigation of the behavior of concrete and other cementitious materials under exceptionally high hydrostatic pressures is extremely important for understanding the performance of concrete structures under severe loadings that are caused by nearby explosions, high-intensity impacts, and projectile penetrations. One of the key characteristics of this behavior is the equation of state (EOS) that is the relationship between the hydrostatic pressure and the density. This equation must take into consideration bulk plasticity and strengthening that are caused by micro-pores closure [1,2].

However, this problem has not yet been adequately investigated, and therefore the mechanisms of bulk deformation and damage that are developed within that range of high pressures are far from being clearly understood. This is partly because the application of controlled extreme pressures requires special equipment and expensive experimental setups and the testing process is associated with a wide variety of technical problems.

There exist two major techniques to obtain the EOS: dynamic and static. The major dynamic techniques are:

1. Using a split Hopkinson pressure bar (SHPB) where the specimen is located within a metallic ring [3,4] or has no confinement [5]. The specimens in most of these tests are relatively small and therefore such tests are focused mostly on mortar specimens [6] and rarely on concrete specimens with small size aggregates [3].
2. Inverse impact planar tests [3,7–10] with a concrete specimen impact on 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 [28].

Another proposed approach to obtain the EOS for concrete that contains coarse aggregates is to implement a mixed analytical-experimental technique. Along with this approach, dynamic tests are carried out on mortar and cement paste specimens and then

* Corresponding author.
*E-mail address:* karinski@technion.ac.il (Y.S. Karinski).

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numerical simulations are conducted on a concrete mixture at a mesoscale level in which the coarse aggregates effect is incorporated in order to obtain the EOS for concrete [11].

Static tests may be performed on larger specimens containing coarse aggregates. Several studies are reported in the literature on either triaxial pressure loading [12–16] or using a uniaxial confined testing technique [2,17,18]. The triaxial loading tests are commonly performed by high-capacity tailor made hydraulic triaxial press machine [19–22]. Specimens that are loaded by pressurized fluid are jacketed with a rubber membrane [15]. These tests allow pressures up to ~600 MPa for relatively large concrete specimens. The uniaxial confined (oedometric) tests are more affordable and provide quality results at this high-pressure range. Utilization of uniaxial strain tests to such pressure levels under confinement conditions [2,23] may apply very high pressures and develop relatively large deformations of the specimen. In such uniaxial strain tests, the state of stress combines a major hydrostatic component with a deviatoric component. Because of the dilatancy of cementitious materials under deviatoric loading [24,25], uniaxial strain tests cannot be directly used to determine the EOS. However, after calibration of the mixture bulk modulus, these tests may be used for verification of theoretical models of the equation of state [26,27].

In an earlier study, the authors have developed the first generation of a multi-scale mix based model for unsaturated cementitious materials [26,27] and have validated the proposed model for small specimens (30 mm diameter) made of cement paste and mortar in confined tests with high pressures up to 300 MPa [18,29]. However, the small experimental apparatus that had been developed for that purpose, did not allow reaching the pressure levels at which bulk hardening begins, i.e. the level which is associated with the closure of a significant portion of the capillary pores in the cement paste.

This paper aims at presenting the following recent development of study in which an experimental setup to perform confined compression tests of cement paste, mortar, and concrete specimens at high pressures up to 850 MPa has been developed and further validation of the proposed theoretical model for these high-pressure levels has been carried out.

## 2. Materials and setup

### 2.1. Mix proportions

Mortar mixes with water to cement (w/c) ratio of 0.50 and various content of natural quartz sea sand were tested. The cement used in this research was a Portland cement of CEM I 52.2 N type. The chemical composition of the cement can is given in Table 1.

Different mortar compositions were prepared with fine aggregate contents of 15, 30, and 45% by volume (subsequently they are indicated as M50/15, M50/30 and M50/45, respectively). Table 2 presents the compositions of the mortars mixes per 1 L. In this series of tests, fine aggregate that is passing a sieve size of 1.18 mm was used.

The same compositions had been used in the earlier tests on small specimens [18,29]. This allows a comparison of the previous and present test results and a study of the size effect under these test conditions (see Section 4.2).

### 2.2. Experimental setup and specimens

The new experimental apparatus that has been built for testing the behavior of the present larger cylindrical specimens to high confining pressure is shown in Fig. 1a.

The apparatus is made of the high strength steel thick-walled hollow cylinder of 180 mm height and with internal and external diameters of 70 mm and 150 mm, respectively. The load is transmitted to the specimen by means of a steel piston of 70 mm diameter and 165 mm height (Fig. 1b). The apparatus is placed on a 40 mm height heavy base of the 150 mm diameter that is shown in Fig. 1c.

To place the specimen centrally in the test apparatus and to avoid the effect of friction between the basement and the specimen the tested specimen is placed on a 70 mm diameter, 14.5 mm height, high strength steel spacer (Fig. 1d). A 5000 kN hydraulic press was used to apply the axial vertical load on the specimen.

The cement paste, mortar, and concrete specimens were cast into cylindrical forms of 69.8 ± 0.1 mm diameter and 150 ± 1 mm height. The specimens were stored in sealed conditions, and after 24 h, the specimens were demolded and placed in a water bath for curing. The specimens were kept in a climate-controlled room at the temperature of 20 ± 0.5 °C until the age of 28 days. At the age of 28 days, the specimens were oven dried at 40 °C to constant weight and kept

(a) Assembled apparatus (b) Steel piston

(c) Base (d) Spacer

**Fig. 1.** Photo of the setup.

**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 |

**Table 2**
The composition of the mortar mixes per 1 L.

| Notation | W/C | Sand,% | Cement, g | Water, g | Sand, g |
|---|---|---|---|---|---|
| M50/15 | 0.50 | 15% | 1039.8 | 519.9 | 394.5 |
| M50/30 | 0.50 | 30% | 856.3 | 428.2 | 789.0 |
| M50/45 | 0.50 | 45% | 672.8 | 336.4 | 1183.5 |