A new Hopkinson bar method to investigate the compacting behaviour of fresh concrete

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Abstract. A new experimental test, based on the Hopkinson bar measurement technique is used in order to analyze the compaction process of a fresh concrete under successive impacts. The use of this modified Hopkinson bar technique allows for the measurement of the compacting stresses during one impact. In fact, the measurement device allows to measure the stress/time response of the material during each shock independently. In particular, the study is focused on the analysis of the stress/time curve during the first shock on the freshly-mixed concrete specimen. It happens that the stress response exhibits the occurrence of the equivalent of a phase change for the granular material. It is therefore possible to measure at what moment this phenomenon happens. Then, we show that, considering a model of shock front for the propagation of the compacting wave, the phase change occurs at a density that depends on the impact velocity. The results shows that the increase of the impact velocity leads to an increase of the phase change density.

1. INTRODUCTION

Prefabricated concrete products are widely used in the world and have an important economic interest. They are generally processed by moulding from semi-liquid soft fresh concrete. During the moulding process, the fresh concrete undergoes a compaction up to 60% in order to obtain a good strength of the final products. This compaction is generally performed by a combined action of a compression and an assisting vibration [1]. But in fact, the vibrating system in the industrial manufacturing process in Europe generates successive strikes on the mould containing the products [2, 3]. As a consequence, one point of view is to consider the forming process as a series of independent impulsive low velocity impacts, which is complementary to a smooth sinusoidal vibration assumption. For this purpose, a shock test based on the Hopkinson bar technology has been developed.

Former results of application of this tests showed the global efficiency of successive impacts compared to a quasi-static compacting process [4]. The study presented here is focused on what happens during one impact, and in particular during the first impact. In a first section, the studied material and the experimental device are presented. In a second section, the experimental measurements performed during each successive shock are given. The results show that the material undergoes somehow a phase change. Thus, a modeling of the compacting process is given, based on a shock theory and finally the dependency of the densification density versus impact velocity is stated and discussed.

2. DESCRIPTION OF THE TEST

2.1 Material

The studied material is a particular fresh concrete for industrial use, which formulation is the following (in wt% of dry material): granulates 35%, sand 57.3%, cement 7.7% and water 7.3%. The granular phase (aggregates and sand) is polydisperse: grain sizes range from 0 to 6 mm. All the grains are dried at the ambient atmosphere before mixing during 2 min. The material is introduced into the mould in a "rain" way. During the test, the specimen of fresh concrete is cylindrical, of constant diameter 62 mm, and initial height 200 mm. The initial density of the specimen is about 1450 kg/m^3.

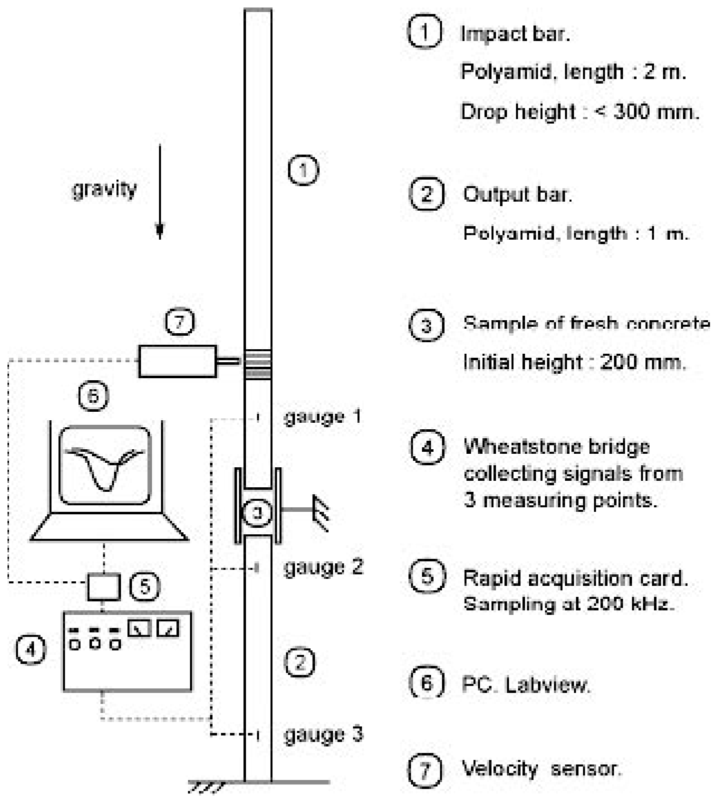

Figure 1. Experimental device.

2.2 Experimental device

Hopkinson bar measurement technology was introduced by Hopkinson [5] and applied to material testing by Kolsky [6]. Generally used in order to test solid materials, it also serves for soils studies [7].

The device is a vertical nylon Hopkinson bar apparatus that was described and validated in a former paper by the authors [4]. The configuration of the test is depicted in figure 1. The test consists in dropping several times the impact bar onto the specimen in order to compact it (see figure 2). Fresh concrete is introduced in a vessel fixed to the structure so that it is directly crushed between the impact bar and the transmitter bar during one test. The measurements given by the bars allow to determine, during the whole shock length, stress and velocity at the interfaces specimen/bars. The fact that the measurement is performed on both sides of the specimen allows to measure the time for the compression wave to travel across the specimen. Regarding the processing of the measured signals, a shift is applied in order to determine the values at the interface. In fact, the duration of the compaction is longer than the measuring capacity of the bars when a classical processing is performed [8]. Then a special shift algorithm is applied to extend the measuring time of the bars [9].

The configuration of this experiment can be viewed as a reproduction of the “Proctor” compaction tests used classically in soils mechanics [10]. In this test, the only measurements are the energy of the falling mass performing the compaction and the resulting apparent density of the specimen. In our experiment, the Hopkinson bar give additional stress measurements.

3. RESULTS AND DISCUSSION

3.1 Experimental results

The basic measurement is the variation of the apparent density following an impact. It is the measurement of the apparatus considered as a pseudo-Proctor test. The main noticeable result is that

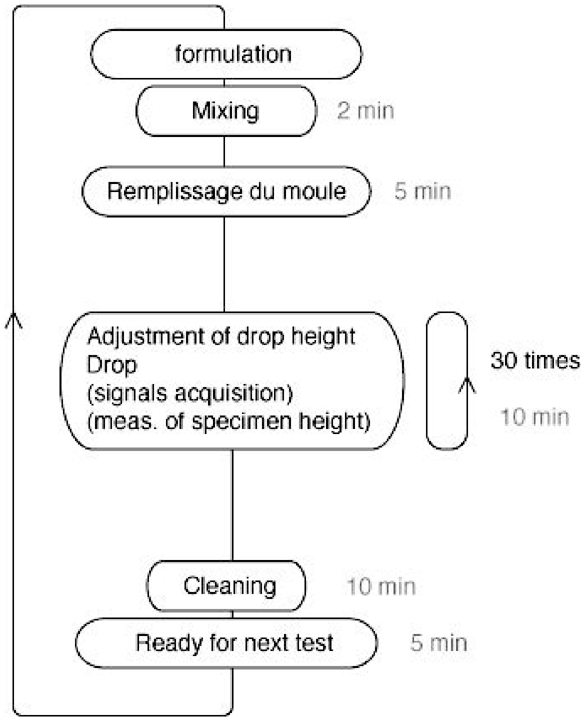

Figure 2. Procedure for one test.

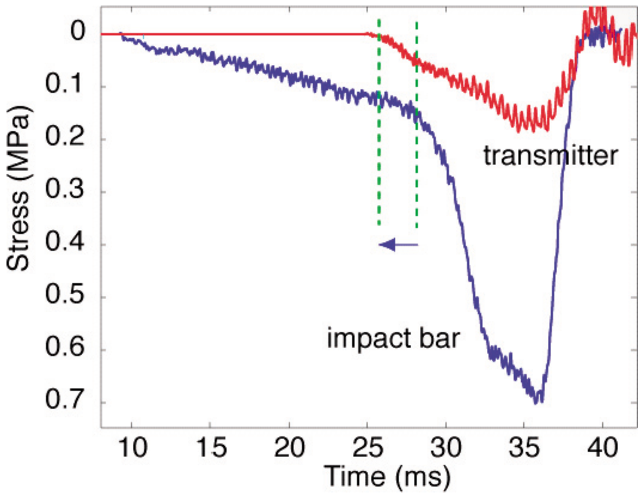

Figure 3. Stress measurements for the first impact.

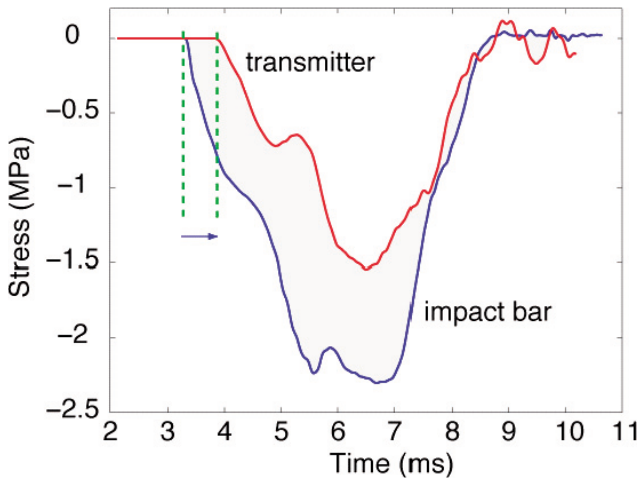

Figure 4. Stress measurements for the fifth impact on the same specimen.

55% of the total compaction is achieved during the first impact. For every following impact, the increase in apparent density is less than 6%.

The additional results given by the Hopkinson bars are the following. Figure 3 shows the stress response measured on both sides of the specimen for the first impact. The stress is calculated as the nominal stress, the cross-section of the specimen remaining constant. Figure 4 shows the measurements but during the fifth impact of the series applied on the same specimen. It is mentioned that the analysis given about figure 4 is also applicable to every result measured from impacts 2 and next.

The comparison of the figures 3 and 4 shows that the first impact is qualitatively different from the others:

- the stress level is at least 3 times lower,
- the impact duration is at least 3 times higher,
- the impact chronology is different: a large plateau of almost zero stress, then a sharp increase and thenafter the unloading. For the others, there are two successive sharp loadings before the unloading,
- the sharp increase of the stress occurs first on the transmitter bar and then on the impact bar, whereas for the other impacts is it the contrary.

3.2 Discussion

The observations are explained by assuming that the material undergoes, during the first impact, somehow a phase change. In fact, it is considered that before the sharp increase of the stress, shown in figure 1, the material behaves like a highly compressible fluid-like material. It is relevant because the freshly–mixed material is very loose and has almost no cohesion. After the sharp increase, the material behaves like a weakly compressible solid-like material. The transition between the two states is considered to be a phase change. This assumption is linked to a phase transition classically observed in model granular materials [11].

Experimentally, we observe that this phase change occurs during the first impact. This justifies the fact that the stress response is different between the first impact and all the others. Supposed explanations can therefore explain all the observations made in section 3.1, and in particular the fact that the sharp increase of the stress happens on one hand on the impact bar first and on the other on the transmitter bar first:

- the plateau at almost zero stress must correspond to the propagation of the phase change in the height of the specimen. The stress is almost zero because the initial cohesion of the material is very low and when the first layer of the specimen has turned to solid, it is locked and the following layer is being compacted (figure 5). This phenomenon can be modelled by a shock front theory that is given in next section,
- when the shock front arrives at the interface with the transmitter bar, there is the sharp increase of the stress at this interface. The reflected wave travels across the speicmen and induces the sharp increase on the impact bar some time later,
- for other impacts, the material has a solid-like behaviour and the expected stress response is: the creation of a compression wave by the impact bar, shown by the increase of the stress at this interface. Then this wave propagates into the specimen and arrives at the transmitter bar with an increase of the stress some time later. The second loading phase is due to the reflected wave.

3.3 Shock modelling

Contrary to a classical device, the measurement of the stress history during the first impact allows to observe somehow a phase change and to propose a compaction process. We supposed, in former section, that the phase change of the material propagates into the specimen as a plane shock front in the sense that there is a moving discontinuity of the state of the material. The mean celerity of this discontinuity can be calculated from the duration for the shock front to travel across the specimen, depicted by the plateau length in figure 3.

It is supposed in this modelling that the material has a RPPL (rigid perfectly plastic locking) behaviour [12]. It is consistant with the strenghtening behaviour of the material measured during a quasi-

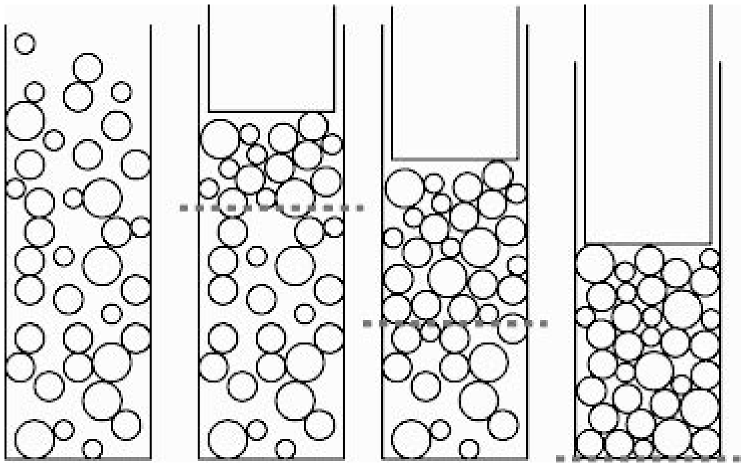

Figure 5. Supposed compaction process during the first impact.

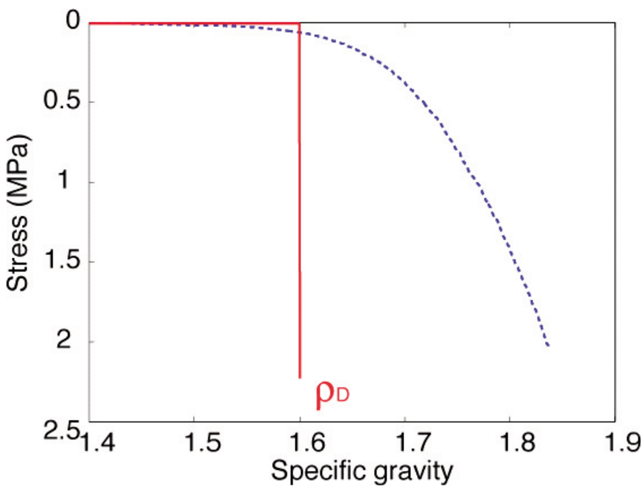

Figure 6. The RPPL model and a quasi-static compression test result.

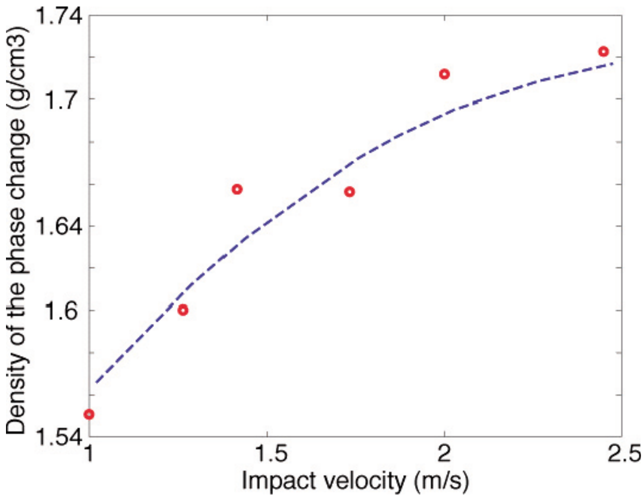

Figure 7. Effect of the impact velocity on the calculated density of phase change.

static compression test (strain rate of 1 mm/s), depicted in figure 6. The locking density ρ_D, corresponds to the phase change mentionned in section 3.1.

The mass conservation at the shock front is written : $$\rho_D(V_i - C_s) = -\rho_0 C_s \quad (1)$$

where V_i is the impact velocity, C_s the celerity of the shock front and ρ_0 the initial apparent density.

In this case we can calculate the expression of the celerity of the shock front : $$C_s = \frac{\rho_D}{\rho_D - \rho_0} V_i \quad (2)$$

It is supposed that ρ_D is actually the unknown and that it is calculated from the measurement of the shock front celerity C_s. The value of the celerity is a mean calculated by dividing the height before the impact by the time when occurs the sharp increase of the stress on the transmitter bar (e.g. it is about 16 ms in figure 1). The locking densities are calculated for different first impacts performed at different impact velocities. The results are shown in figure 7. It is noted that the order of magnitude of the density is relevant with the compression test shown in figure 6. The results show that the increase of the impact velocity tends to increase the density of the phase change of the material.

4. CONCLUSIONS

A new Hopkinson bar method is presented. It is applied to the study of the compacting behaviour of a fresh concrete. In addition to a classical compaction test such as Proctor test, this apparatus allows to measure the stress response of the material submitted to an impact. In particular, it allows to detect the occurence of a somehow phase change. An explanation of the observations is given and leads to a shock front model for the compaction process during the first impact. This model allows to calculate the effect of the impact velocity on the phase change density of the material.

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