A study of the Hugoniot of mortar

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Although concrete and mortar are widely used as raw materials for building construction, there are few studies on their equations of state (EOS). In this paper, the Hugoniot EOS of mortar was measured by piezo-resistive manganin pressure gages. The gage was inserted in two thin Al 6061 plates which were located between two mortar plates or between a sand layer and a mortar plate. The pressure-time profile was analyzed by using the impedance mismatch method, and the EOS data was determined. The obtained Hugoniot was expressed by a linear $U_s - u_p$ relationship; $U_S = 1053 + 3.41\ u_p$, where U_S and u_p are shock and particle velocities (m/s) respectively. The obtained pressure profiles were fairly reproduced by a one-dimensional hydrodynamic computations using this experimentally obtained formula.

1. Introduction

The shock compression technologies have been extensively applied to material synthesis and processing, space science, medical technology and so on[1]. Researches of the equation of state (EOS) under high pressure, in particular, the data of Hugoniot EOS have been reported for many materials[2]. Concrete and mortar, which contains finer aggregate than concrete[3], are widely used as the most basic raw materials for building construction, and are utilized to construct explosive warehouses and nuclear power plants which might be exposed to high dynamic pressures under unexpected accidents. Analysis of such explosion accidents requires detailed knowledge of the characteristics of the materials under dynamic loadings. Blasting these materials in, for example, urban blastings also has a need to know the dynamic response of these materials to intense shock loadings. Hall et al.(1998) reported the EOS of concrete with several aggregate sizes[4] using a velocity interferometric techniques. They derived two equations of concrete for higher and lower stresses parts respectively, based on the data up to 2000 m/s of the particle velocities. Although the properties such as strength, propagation of stress wave and simulations for blasting building structures have been reported in some other papers[5)~8)], there are few studies investigating these EOS. In this work, the EOS of mortar, which is relatively more uniform than concrete, is reported using an impedance mismatch technique with one piezo-resistive pressure gage.

2. Material

Concrete and mortar are a mixture of cement, aggregate, water, and some admixtures for particular properties. According to the particle size, the aggregate is classified to fine aggregate and coarse one. The former is defined that the aggregate passes through 10 mm sieve, and 5 mm sieve more than 85% in weight. The latter stays on 5 mm sieve more than 85%. Mortar is defined as mixture with a fine aggregate for integration[9]. In this work, mortar

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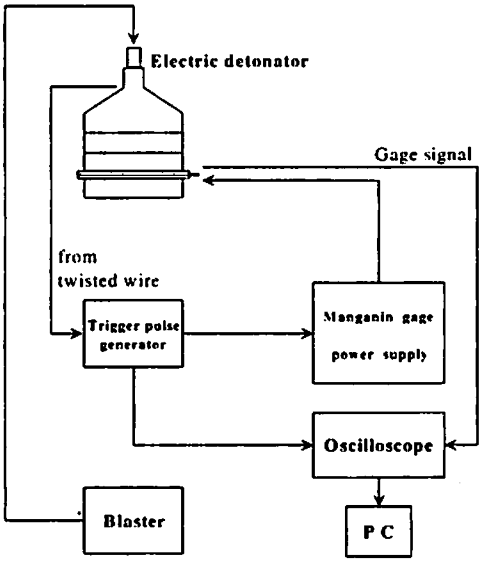

Fig. 1 Experimental block diagram

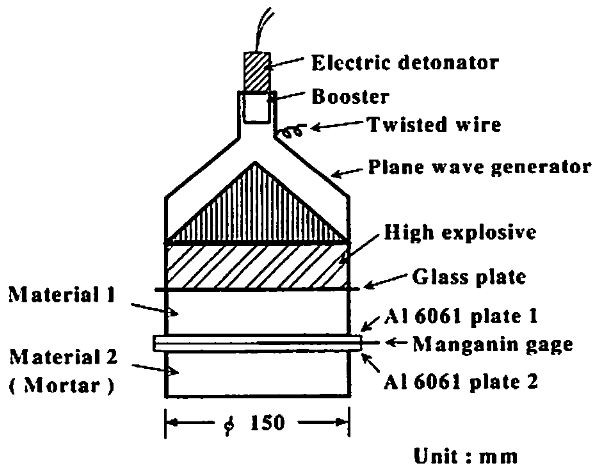

Fig. 2 Illustration of the experimental assembly

plates were made up from ordinary portland cement, sand which passed through the 4.75 mm standard sieve as a fine aggregate, and pure water. The mixture proportion was portland cement : sand : pure water = 1 : 2 : 0.65 in weight. After mixing and molding, the mortar plates were placed for 48 hours and they were covered with wet clothes and sealed up with polyethylene plastic film to keep them moist for curing as long as 28 days. These plates were then polished flatly within ±0.3 mm roughness, and were used for experiments. These average density with 95 % confidence interval was 2080 ± 35 kg/m^3.

3. Experimental and derivation of Hugoniot data

The experiments were performed using piezoresistive manganin pressure gages (MN10-.050-EFEP) manufactured by Dynasen Inc., and their average resistance was 0.04 ohms. The pressure-time profiles were recorded by digital waveform recorders (Sony Textronix RTD 710A). Dynasen CK-3-.050-300 was used for triggered constant current supply, and was set to discharge about 800 mV (under no-compression condition) pulse to the gages for 180-190 μs. The configuration of experimental devices is shown in Fig.1. To obtain the EOS of mortar, the gage was inserted into two 2 mm thick Al 6061 plates whose density $\rho_0 = 2703$ kg/m^3, and the Hugoniot EOS is already known as $U_S = 5350 + 1.34\, u_p$ (m/s), where U_S (m/s), u_p (m/s) are shock and particle velocity respectively[2]. A typical experimental setup is shown in Fig.2. One-dimensional plane shock wave was generated by the plane wave generator. Nitromethane, PBX80RU (RDX 80 wt.%, 1750 kg/m^3), Composition B and mixture of hydrazine nitrate (HN) / hydrazine hydrate (HH) = 75 / 25 wt.% were used for the main explosives[10]. The experimental conditions are listed in Table 1. A pressure-time profile generally has a wave form represented in Fig.3. The pressure P_a in Fig.3 corresponds to the shock pressure propagated from material 1 and Al 6061 plate 1 drawn in Fig.2. P_b is the pressure reflected at the interface of Al 6061 plate 2 and material 2 (over 20 mm thick mortar plate). The pressure vs. particle velocity relationship on P-u_p plane is illustrated in Fig.4 with use of the impedance mismatch method, and the coordinates of the mortar EOS parameter (P, u_p) can be specified. As P_a and P_b are located on the primary and reflected P-u_p curves, respectively, of Al 6061, particle velocities at P_a and P_b are immediately obtained. When the pressure profiles are time dependent, which is not square pulse shape but changing with time, the values just before and after the reflectin point (t_r) are taken as data. The U_S value of mortar at the point P_b can be calculated, since the slant from the origin to a point on the curve in the P-u_p plane is $\rho_0\, U_S$, and the ρ_0 of mortar can be measured. Therefore, the Hugoniot EOS locus of mortar is found out with some mortar (P, u_p) data obtained by the variously changed incident pressure of shock wave. The values of P_a and P_b are obtained

Table 1 Experimental results and obtained shock and particle velocities

Shot No.	Explosives	P_a (GPa)	P_b (GPa)	u_p (km/s)	U_S (km/s)	Material 1 (See Fig. 2)
1	Nitromethane	14. 6	10. 0	1. 07	4. 48	19. 9mm thick mortar
2	Nitromethane	5. 9	3. 3	0. 53	3. 00	30. 0mm thick copper, and 20. 0mm thick mortar
3	Nitromethane	8. 8	5. 4	0. 70	3. 71	19. 9mm thick mortar, and 20. 0mm thick sand layer
4	PBX 80RU	17. 0	12. 4	1. 18	5. 08	20. 6mm thick mortar
5	Composition B	5. 5	2. 7	0. 52	2. 56	46. 5mm thick mortar, and 45. 8mm thick sand layer
6	*HN/HH = 75/25 wt.%	18. 8	14. 1	1. 25	5. 42	14. 5mm thick mortar

*HN is hydrazine nitrate and HH indicates hydrazine hydrate.

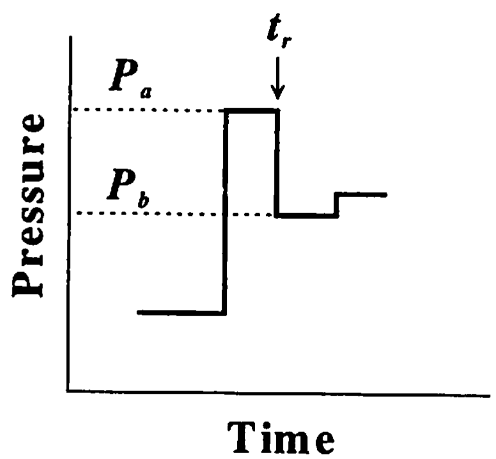

Fig. 3 Observed pressure-time profile of manganin gage

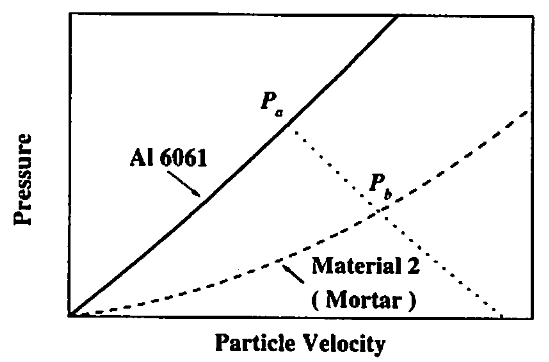

Fig. 4 Illustlation of the impedance mismatch method

to use the observed peak pressures corresponding to each profile. Besides, it is considered that this technique can be applied to obtain the Hugoniot EOS of unknown materials.

4. Results and Discussion

Based on the data listed in Table 1, the obtained U_S-u_p data are plotted on Fig.5. The two segment formula derived by Hall et al.[4], the high pressure part $U_S = 2235 + 1.75\ u_p$ (m/s) and the low $U_S = 551 + 4.52\ u_p$ (m/s), are also plotted. Figure 5 shows all the dots have a good linearity with the coefficient of determination $R^2 = 0.9688$ (R is the correlation coefficient between the observed values and the regression estimates, and R^2 indicates the fitness of the regression function), and the well known $U_S = C + s\ u_p$ relationship, the Hugoniot EOS of mortar, can be determined as

$$U_S = 1053 + 3.41\ u_p \ \text{(m/s)} \tag{1}$$

The difference between the equations of this work and those of Hall et al might be attributed to the aggregate size, because they focused on the concrete which contains coarser aggregate. Although the effect of aggregate size is still unknown,

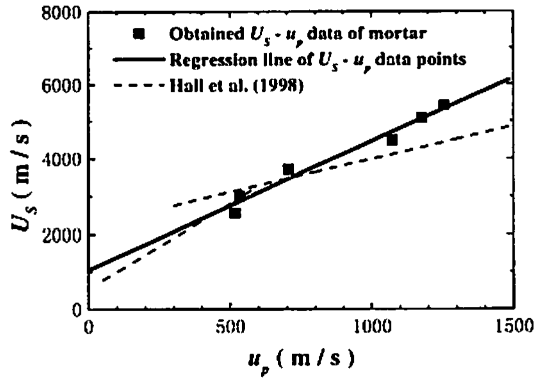

Fig. 5 U_S-u_p Hugoniot of concrete and mortar. Solid line is the relationship for mortar determined by this work. Dashed lines indicate the relationship for concrete derived by Hall et al. (1998).

the relationship derived by this work fits well the obtained data. Using the Hugoniot EOS of (1) and the Mie-Grüneisen EOS, we carried out numerical simulations with one-dimensional Lagrangian hydrodynamic code[11]. The Grüneisen coefficient Γ of mortar was estimated by $\Gamma \approx 2s-1$. In the simulation, the explosives used for the plane wave generator were changed to the equivalent nitromethane in weight. The total mesh number was set around 700. Figures 6 and 7 show the observed pressure-time profiles and simulated results for the shot No.1 and 4 respectively. It seems that the simulated result for shot No.1 agrees with the observed profile comparatively. In Fig.7, the observed stress is gradually increasing behind the shock front of first steep rising up, and is separate from the simulated result. The stress wave peaks corresponding to P_a and P_b at the time t_r (see Fig.3) match the simulation and the agreements of both lines are generally good. It is supposed that this observed phenomena is attributed to considerable wave structure in the heterogeneous material, that is, the grains and the grout will cause different particle velocities and will occur many reflections of the stress wave at the contact surfaces. The forms of stress wave illustrated in Fig.6 and 7 were different, so it might be possible that the EOS was changed at threshold pressure around 15～16 GPa. The existence of the process of relaxation for wave propagation due to the material structure can not be rejected, too. Although the microscopic phenomena can not be

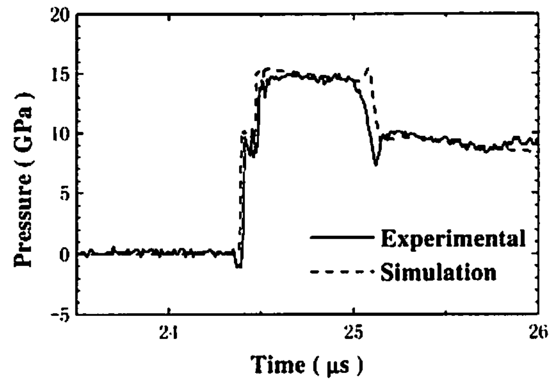

Fig. 6 Comparison of experimental and simulated result for shot No.1

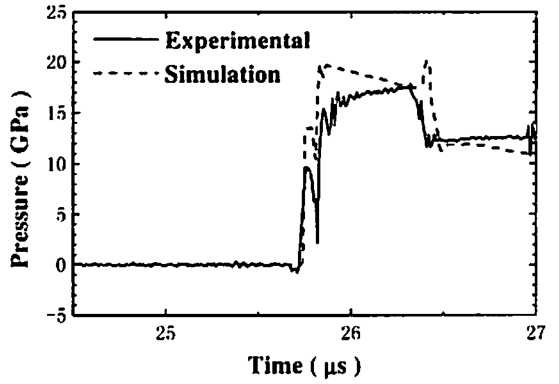

Fig. 7 Comparison of experimental and simulated result for shot No.4

answered explicitly now, it seems that the quantity of state under shock compression of mortar could be simulated well comparatively. Besides, the proposed technique can be applied to obtain the Hugoniot EOS of unknown materials, and it is useful for blasting, designing of particular purpose construction and so on.

Our lowest pressure data exist at around the highest pressure portion of the lower fit of the two fits of Hall et al. and the existence of different EOS relationship at lower pressure for our material should be answered by further experiments at lower pressure regime.

5. Conclusion

In this work, using piezo-resistive manganin gages inserted between thin Al 6061 plate whose Hugoniot EOS is already known, we derive U_S-u_p relationship of mortar as $U_S = 1053 + 3.41\ u_p$ (m/s). On the simulation results with one-dimensional Lagrangian hydrodynamic code, we obtain comparatively good agreement to the experimental pressure-time profiles. On account of the possibility of the existence of changing Hugoniot point, it is necessary to check up the response for the more higher and lower pressure area. To determine how the heterogeneous nature of concrete and mortar influences the decay of the shock, pulse attenuation studies would be appropriate to pursue for these materials. The effect of the aggregate size and acquisition of the Hugoniot EOS of the aggregate (sand) which might be attenuable material is also a future investigation.

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モルタルのHugoniotに関する研究

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コンクリートやモルタルは堅固な建築材として幅広く用いられているにも関わらず，衝撃圧縮下での状態方程式に関する研究は極めて少ない。本研究は，マンガニンピエゾ抵抗ゲージを用いてモルタルの状態方程式を実験的に求めた。モルタル板の間もしくは砂の層とモルタル板の間に，状態方程式が既知であるAl 6061を介してゲージを設置し，圧力プロファイルの観測をおこなった。測定されたピーク圧力にインピーダンスミスマッチ法を用いることによりモルタルの状態方程式データを導き，$U_S=1053+3.41\,u_p$ (m/s)という直線関係を得た。さらに1次元ラグランジュ流体計算コードによる圧力伝播シミュレーションをおこない，実験データと比較的良好な一致を得た。

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