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Impact response of lightweight mortars containing expanded perlite

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ABSTRACT

This paper describes the mechanical response of lightweight mortars subjected to impact loading in flexure. Expanded perlite aggregate with a bulk density of 64 kg/m^3 was used at between 0 and 8 times by volume of Portland cement to yield a range of mortars with density between 1000 and 2000 kg/m^3. Some specimens were reinforced with a polypropylene microfibre at 0.1% volume fraction and the dynamic fracture toughness was evaluated by means of an instrumented drop-weight impact system. Companion tests were carried out in compression under quasi-static loading to standardise the mixes. The compressive strength and elastic modulus scale as the cube of the relative density, defined as the ratio of the density of the mortar to that of Portland cement paste. Whereas the flexural strength and fracture toughness were both linearly proportional to the relative density of the mortar under quasi-static loading, there was an increase in their sensitivity to relative density at higher loading rates. Contrary to what is seen in regular concrete, fibre reinforcement led to an increase in the stress-rate sensitivity of flexural strength in lightweight mortars. For the same impact velocity, the stress-rates experienced by a specimen was strongly influenced by its density. While the stress-rate sensitivity of flexural strength dropped with a decrease in the mix density, that of the fracture toughness was consistently higher for the lighter mixes.

1. Introduction

Perlite is an amorphous form of rhyolitic or dacitic magma that contains 2–5% water [1]. It transforms into a lightweight cellular material when heated to between 900 and 1000 °C. Its use in structural elements has been promoted in dynamically loaded members, where in the resulting reduction in the reactive mass is expected to limit the effect of earthquakes [2]. In most applications, it has been used as a replacement to Portland cement as a lightweight microfiller or to replace a portion of the sand. While its pozzolanic activity is acknowledged [3], its role in lightweight mortars is largely that of an inert aggregate [4].

Low density cement based composites may be divided into two categories: lightweight aggregate cementitious composites and foamed cement based composites. The former may further be classified into structural lightweight concrete and non-structural mortars (used mainly as insulation). Of these, foamed cement composites and non-structural mortars have crash cushioning abilities due to the manner in which they dissipate energy. An ideal shock absorbing material must possess high deformability, where the crushing strength is only important as a lower limit to the thickness of the barrier. Fig. 1 describes the typical load-deformation response of cellular solids [5], where the crushing strength is relatively low, but the composite is vastly deformable. The crushing strength is related to the buckling strength of the cell wall [6] where as overall deformability is related to the fracture toughness of the material in the cell wall. The plateau region in Fig. 1 describes the energy absorbing capacity in solids with significant cellular microstructure.

In designing cement based impact attenuators, lightweight, cellular inclusions such as expanded polystyrene, vermiculite and air bubbles have been used with varying degrees of success [7]. Recently, Le et al. [8] described damage due to high strain rates in high strength lightweight concrete. While lightweight aggregate concrete made with expanded perlite and vermiculite have been examined for shock absorption as far back as the 1960s [9], the quantification of material properties under dynamic loading has been limited with no information on their stress rate sensitivity and related dynamic fracture parameters. Further, much advancement has taken place in the succeeding decades through the introduction of short fibres for reinforcement. Both in conventional concrete and in structural lightweight concrete, such discrete fibre reinforcement is known to impart resistance under impact loading [10]. Where as steel fibres are most common in structural concrete, fibres such as those of glass, polypropylene and cellulose are known to perform better in controlled low strength materials, due to the compatibility in their strength and moduli [11].

This report is a part of a program to develop controlled low strength shock absorbing cement based composites for applications including rendering mortars, tunnel liners and similar protective construction through a suitable combination of modern

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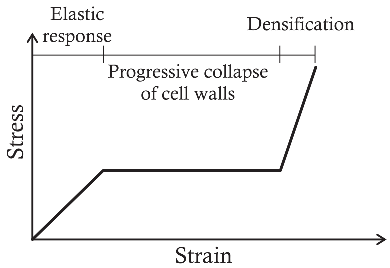


Fig. 1. Load-deformation response for an ideal energy absorbing material.

lightweight materials. The authors investigated controlled low strength lightweight mortars containing expanded aggregate fillers and polymeric microfibres. Specifically, the stress rate sensitivity of a range of lightweight mortars is examined through flexural testing of notched beams and the mechanical properties are related to the density of Portland cement paste.

2. Experimental details

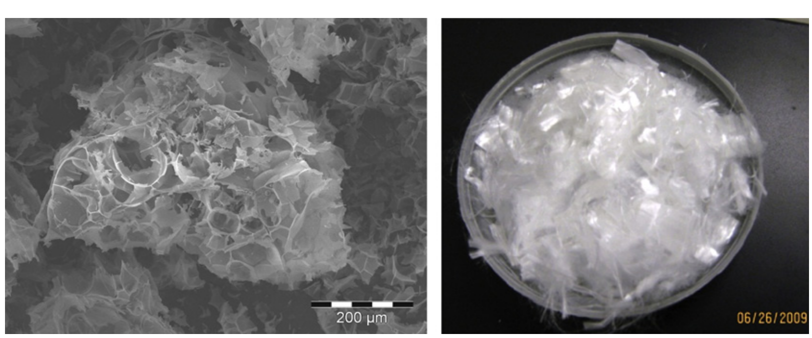
2.1. Materials and mixes

Plain, unreinforced mixes were cast at four densities to examine a range of lightweight mortars between 1000 kg/m^3 and 2000 kg/m^3. The heaviest was effectively a cement paste that served as the reference, containing only Portland cement and a water-to-cement ratio of 0.4. Type GU Portland cement [12] as obtained from local suppliers was used in each mix. The remaining three lower densities were cast with increasing amounts of expanded perlite. The expanded perlite was sourced from a volcanic glass heated to 870 °C, resulting in a light weight material possessing a high specific surface area with properties as shown in Table 1. It had a bulk density of 64 kg/m^3 with a maximum particle size of 1.68 mm. As seen from Fig. 2a, the microstructure is characterised by open pores (small channels that form a thick network) and closed pores (isolated cells and holes). The simultaneous presence of these morphological features gives the mineral an extremely high transpiring power, due to the open pores, and at the same time, some crushing resistance in comparison with other lightweight fillers such as expanded polystyrene, due to the closed pores [13]. The former has led to its use in thermal insulation, while the latter has been utilised in structural lightweight concrete. In the present study, the addition of expanded perlite lightweight aggregate (EP) was defined by a volumetric ratio of EP with respect to Portland cement (PC), so that together with the reference mix, four mixes with volumetric ratios of 0, 0.8, 4, and 8 were produced. In order to be consistent with the water-to-cement ratio, a mini-slump cone was utilised to conduct a slump test (Fig. 3). The mixes were prepared to achieve a slump spread between 130 and 190 mm. Since the expanded perlite beads absorb a significant amount of the water added to the mix, an increase in the perlite content was compensated by a corresponding increase in the mix water. Accordingly, the water-to-cement ratio was 0.4 for the reference mix, and also for those containing volume ratio of EP-to-PC equal to 0.8 and 4. For the lightest mix with a volume ratio of EP-to-PC of 8, the water-to-cement ratio was raised to 0.8.

Polymeric microfibres were chosen as discrete reinforcement due to their low modulus and high aspect ratio. The mixes in this investigation contained no coarse aggregate and as is well known, lightweight cementitious composites tend to be more brittle [14,15]. Therefore, an additional three mixes were reinforced with polypropylene microfibres that were 20 mm long with a maximum Denier count of 3 (in g/9000 m) and an elastic modulus of 3450 MPa (Fig. 2b). In order to retain adequate workability, a relatively low fibre volume fraction of 0.1% was considered. As there was no significant change in density for EP/PC equal to 0.8, only the reference cement paste and the two lightest mixes were reinforced with fibres. In spite of the low fibre content, workability continued to be a concern for the fibre reinforced mixes that also had expanded perlite. Hence, a combination of water reducing and/or air entraining admixtures were added to these mixes. In all cases, the mixes were designed for similar workability as expressed by the mini-slump cone test. Table 2 lists the mix designation and proportions for all seven mixes. Cylinders were cast to have 100 mm diameter and 200 mm height, while prisms were cast at 100 mm width × 100 mm height × 400 mm length to serve as beam specimens in flexure. The specimens were demolded after 24 h and placed in a curing chamber with controlled temperature (25 ± 2 °C) and humidity (100 ± 5% RH). The prisms were sawn to have notches 2 mm wide and 10 mm deep, to enable a study of crack growth. In each instance, at least six cylinders and beams were tested to produce the average data point for further analysis.

Table 1
Properties of expanded perlite used in this study.

Property	Value
Colour	White
Specific gravity	2.34
Bulk density (kg/m^3)	64
SiO_2 (%)	70–75
Al_2O_3 (%)	12–18
K_2O (%)	4–5
Na_2O (%)	3–4
CaO (%)	0.5–2
Fe_2O_3 (%)	0.5–1.5
MgO (%)	<0.5



(a) SEM Image of Expanded Perlite (b) Polymeric Microfibre

Fig. 2. Lightweight aggregate and fibre reinforcement.