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Experimental investigation of the size effect of layered roller compacted concrete (RCC) under high-strain-rate loading

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HIGHLIGHTS

- Dynamic size effects on the properties of RCC material have been investigated.
- Statistical correlation between strain-rate and size effects on RCC is analyzed.
- A modified Weibull size effect law for RCC is proposed considering strain-rate effect.

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ABSTRACT

The strain rate and specimen size are two main influential factors when measuring the compressive strength of concrete-like materials. Understanding the dynamic size effect of concrete is essential for better analysis and design of concrete structures. However, few systematic laboratory tests have investigated the dynamic size effect in layered roller compacted concrete (RCC) under various levels of high-strain-rate loading. In this study, three sizes of cylindrical RCC specimens with diameters of 50 mm, 75 mm and 100 mm are prepared and tested under high loading rates to directly investigate the size effects. The size dependence and strain rate sensitivity are characterized in terms of the failure pattern, dynamic compressive strength, ultimate strain, maximum strains, and toughness. The dynamic compressive strength increases with increasing specimen size under impact loading, which is opposite to the size effect under static loading. The statistical significance is further investigated in terms of the variation in the dynamic mechanical properties of the RCC material based on analysis of variance (ANOVA). A modified Weibull size effect law, which incorporates both the specimen size and strain rate, is proposed and verified to illustrate the underlying mechanism of the dynamic size effect for the RCC material under impact loading.

1. Introduction

It is well accepted, based on experimental and theoretical investigations, that the mechanical response of concrete-like materials under compression, shear, tension and torsion under quasi-static loading is significantly affected by the specimen size. Generally, a smaller specimen requires higher stress to fracture under quasi-static loading. The mechanism of the concrete size effect law for the quasi-static strength can be classified into three categories: (1) Weakest-link hypothesis [1,2]: larger structures have a larger chance of containing a critical flaw that can cause complete collapse, and the structure will fail as soon as the first critical defect fails; (2) Energetic (deterministic) mechanism [3–6]: two fundamental causes of the size effect in concrete structures are the material heterogeneity and the stress discontinuities at the crack tips, which cause stress redistribution and stored energy release (i.e., strain energy dissipation) during the development of macro-cracks; (3) Fractal mechanism [7]: the roughness of the crack surfaces in concrete exhibits inherent fractal characteristics. When the microstructural disorder and self-similar features (i.e., fractality) dominate the damage and fracturing process, the fractal mechanism permits better interpolation of experimental data than the energetic mechanism.

However, when exposed to high-strain-rate loading, concrete-like materials have a higher dynamic compressive strength than their corresponding static compressive strength [8–11]; the fracture energy is also increased [12]. The experiments conducted by Elfahal [13] and theoretical analysis by Qi [14] indicate that the

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Nomenclature

f_d	dynamic compressive strength (MPa)
f_c	quasi-static compressive strength (MPa)
$\Delta f_{\dot{\varepsilon}}$	dynamic strength increase from the material strain-rate effect (MPa)
Δf_i	dynamic strength increase from the structural effect (MPa)
A_{s0}	initial cross-sectional area of the specimen (mm^2)
A_s	real-time cross-sectional area of the specimen (mm^2)
H_{s0}	initial thickness area of the specimen (mm)
H_s	real-time thickness area of the specimen (mm)
$\sigma_s(t)$	engineering stress of the specimen (MPa)
$\varepsilon_s(t)$	engineering strain of the specimen (mm/mm)
$\dot{\varepsilon}_s(t)$	engineering strain rate of the specimen (/s)
c_b	wave propagation velocity in the steel bars (m/s)
A_b	cross-sectional area of the steel bars (mm^2)
E_b	elastic modulus of the steel bars (GPa)
$\varepsilon_T(t)$	transmitted strain in the steel bars (mm/mm)
$\varepsilon_R(t)$	reflected strain in the steel bars (mm/mm)
F_0	corresponding critical value at the 5% significance level
P	cumulative probability density of the failure for a specimen
σ	peak strength of the specimen (MPa)
σ_0	scaling value in Weibull distribution concerned with the mean (MPa)
m	shape parameter or Weibull modulus
$\bar{\sigma}$	mean strength (MPa)
s	standard deviation (MPa)
$\Gamma(*)$	gamma function
N	total number of tests
i	current test number
V	volume of the specimen (m^3)
V_0	average volume of each microcrack (m^3)
σ_{th}	threshold strength of the failure for the specimen (MPa)
σ_1	scaling value in the Weibull size effect law (MPa)
$\dot{\varepsilon}_0$	critical strain rate of the specimen (/s)
α	strain-rate correction factor in the modified size effect law

size effect under impact loading is notably different from the well-known static size effect, in which the dynamic strength increases with the increasing sample size (in terms of the diameter) at a similar strain rate. Moreover, larger specimens display a more significant strain-rate effect. As is known to all, the interpretations of the strain-rate effect on material strength clearly include three main aspects: (1) Lateral confinement effect [15–17]: the lateral inertial force from Poisson's effect and end friction can restrict the lateral deformation of the specimens; (2) Evolution of the cracks [10]: cracks can form and propagate in coarse aggregates under impact loading instead of simply initiating and propagating in the interfacial transition zone (ITZ); (3) Viscosity effect [10]: the movement of free water in micro-defects within the concrete results in resistance to crack propagation under dynamic loading. However, the interpretation and application of the dynamic size effect are still unclear, i.e., the mechanism of strength enhancement for larger structures under dynamic loading, and the application of laboratory testing results from small structures to real full-scale structures.

Based on the concept of the size effect from Vliet [18,19], the size effect can be considered a combination of the material size effect caused by material heterogeneity and the structural size effect induced by the boundary and shape of the specimen. Similarly, the dynamic strength enhancement of concrete under high-speed impact loading consists of contributions from the material strain-rate effect (which occurs due to the inherent microstructure and crack propagation in aggregates and is considered part of the material size effect) and the structural effect (which occurs due to the lateral confinement and end friction and is considered part of the structural size effect) [20–22]. Under this view, the dynamic increase factor (DIF) obtained from the experimental tests can be expressed as

$$DIF = f_d/f_c = (f_c + \Delta f_{\dot{\varepsilon}} + \Delta f_i)/f_c \quad (1)$$

where f_d is the dynamic compressive strength; f_c is the quasi-static strength; $\Delta f_{\dot{\varepsilon}}$ is the dynamic strength increment due to the material strain-rate effect; and Δf_i is the dynamic strength increment due to the structural effect [22].

With respect to the material size effect, many types of microstructure analysis have been conducted to further understand the macroscopic failure phenomena occurring under impact loading [23,24]. The size effect in concrete has been investigated using Monte Carlo simulations of mesoscale finite element models in which the random inclusions (aggregates and pores) with the prescribed volume fractions, shapes and size distributions are considered [25]. It has been confirmed that the mesoscale heterogeneity, aggregate volume fraction and porosity should not be ignored in the size effect studies of concrete [1,26,27]. The structural size effect on the compressive strength enhancement of the concrete-like material in split Hopkinson pressure bar (SHPB) tests has gained the attention of many researchers. The factors responsible for the structural effects include the material parameters (i.e., hydrostatic dependence and dilation parameter), specimen geometry (i.e., diameter and aspect ratio), end interface friction and material inertia [28].

Much effort has been devoted to explain the relationship among the strength, strain rate and specimen size in the context of the complex micro-structural hierarchy and finiteness of the crack propagation speed [14,29,30]. Although the material strength enhancement under impact loading has been proven to be size-dependent, the size effect on other dynamic material properties at different strain rates remains unclear. Moreover, the size effect law for concrete-like materials is not fully understood under impact loading, resulting in an urgent need to extend size effect law to the full range of strain rates, applicable to both static and dynamic loadings.

Roller compacted concrete (RCC), as a special type of concrete material, has different mixture from traditional concrete, i.e., less water and more fly ash are used to replace Portland cement. The mechanical properties of RCC show higher discreteness in the vertical direction due to the construction technology of thin-layer pouring and vibration rolling [31]. To investigate the dynamic size effect of the RCC under high-strain-rate loading, the actual construction technology was replicated in the laboratory, and RCC specimens were prepared for SHPB tests. The size effect cannot be decoupled from the inherent scatter of strength [1,32], which necessitates the use of a statistical method to estimate the size effect on the strength of concrete and on the damage/fracture process in general. In total, 101 cylindrical specimens with identical length-to-diameter (L/D) ratios of 0.5 but different diameters