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# Compressive behavior and constitutive model for roller compacted concrete under impact loading: Considering vertical stratification

She-rong Zhang [a,b], Xiao-hua Wang [a], Chao Wang [a,b,*], Ran Song [a], Heng-yan Huo [a]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China

## HIGHLIGHTS

- The dynamic compressive behaviors of RCC have been investigated by SHPB test.
- Three kinds of failure patterns of RCC are analyzed qualitatively and quantitatively.
- The distributions of dynamic mechanical properties are analyzed statistically.
- A new constitutive model is proposed to describe the dynamic behaviors of RCC.

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## ABSTRACT

This paper presents fundamental investigation on the dynamic compressive behavior and constitutive model of roller compacted concrete (RCC) at intermediate strain rates. Dynamic uniaxial compression tests of RCC specimens were performed by split Hopkinson pressure bar (SHPB). Then, the dynamic compressive properties of RCC material under intermediate strain rate are investigated in terms of failure pattern, stress-strain curve, dynamic increase factors (DIF) of compressive strength, Young's modulus and critical strain at peak stress. The polynomial fitting method (in terms of $\lg \dot{\varepsilon}$) was well adapted to describe the empirical strain rate effect. The vertical stratification of RCC caused by different mix proportion and compacted layer structure has influence on its dynamic mechanical behavior. Due to the statistically discreteness of RCC material, the distributions of dynamic mechanical properties were analyzed with statistics theory. A new statistical constitutive model was proposed with statistical analysis, in which the two main parameters were related to strain rate and conventional mechanical properties. Finally, the developed constitutive model is verified and demonstrated to be high applicability to RCC material and improves the estimations of the dynamic mechanical properties of RCC.



## 1. Introduction

As a special kind of concrete material, roller compacted concrete (RCC) is widely used in constructions of hydraulic structures, transportation and highway engineering facilities. It has essentially the same material component as conventional, but in different mix proportion, such as much less water and relatively more fly ash to replace Portland cement. The mixture is much drier with no slump, spread by bulldozer, then compacted by vibratory roller, and this construction technology is conducive to rapid pouring of mass concrete. It was exciting that the revolutionary use of RCC has promoted rapid progress of dam construction since the initial application in the construction of the Alpa Gera Dam [1]. To properly design the structures using RCC material during design working life, it is important to understand the mechanical properties under all types of loadings, especially dynamic loading arising from natural or man-made disasters such as earthquake and explosion, and there are still many problems to be solved.

The significant differences between RCC and conventional concrete in mechanical properties may come from the different mix proportion and compacted layer structure. Recently, the experiments on RCC material pay more attention to the compaction effect and the material physical properties under quasi-static loadings, such as seepage characteristics [2], mechanical properties between two adjacent layers [3,4], temperature field and temperature control [5,6], aggregate size effect [7], construction process, quality control [8,9], and so on. Moreover, some scholars began to investigate the mechanical properties from mesoscopic to

* Corresponding author at: School of Civil Engineering, Tianjin University, Tianjin 300072, China.
*E-mail address:* janson126@163.com (C. Wang).

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macroscopic, and have achieved certain results, for example, the effects of RCC components on the mesoscopic structure [10] and the compaction mechanism of RCC mixture [11]. In a word, the construction technology of thin layer pouring and vibration rolling results in a layered structure in the horizontal direction, as shown in Fig. 1. It is easy for transition layers to become relatively weak surface if processed improperly or time interval is inappropriately controlled. Therefore, RCC has higher dispersion in vertical direction and the horizontal layer is considered to be isotropic in the analysis of mass RCC structures.

For the dynamic mechanical properties, concrete-like materials under intermediate-high strain rates are generally studied with Split Hopkinson pressure bar [12–16]. The rate-dependent compressive behavior and elastic modulus is characterized by different experiments [12,17]. Also, the critical strain defined as the strain at peak stress is also drown on the strain-rate effect and independent of the water-to-cement ratio [18]. Hao et al. present a state-of-the-art review about the influencing factors in dynamic testing on concrete-like materials [19] including the lateral inertia effects, the contribution of coarse aggregates and the influence of moisture condition. However, the experiments on the RCC material under intermediate-high strain rates are relatively limited and the statistical property of testing results has seldom been taken into consideration. As a matter of fact, all kinds of factors, such as mixing materials, mix design and layered structure, will lead to significant differences between RCC and conventional concrete in mechanical properties. As a consequence, it is urgent to carry out a series of fundamental experiments to reveal the dynamic mechanical properties of RCC under intermediate-high strain rate.

Nowadays, a variety of dynamic constitutive models for conventional concrete have been developed and implemented within various theoretical frameworks under impact loadings. Generally, five major categories can be divided [20]: (a) phenomenological models based on statistical regression analysis of test results. (b) Micromechanical models associated with the concepts of the microscopic properties and damage accumulation. (c) Modified models introducing dynamic correction terms to existing theory. (d) Theoretical models on the basis of thermodynamic laws (e) combinations of the above methods. Numerical simulations have been widely used to study the problems of conventional concrete impact and explosion with the constitutive models of HJC [21], K&C [22], RHT [23] and their modifications [24–26], which take expansion of destruction surface and dynamic characteristics of damage evolution into consideration to describe the dynamic properties of concrete. In the latest literatures, these constitutive models have also been used to the study of dynamic mechanical responses of roller compacted concrete structures under intermediate-high strain rate (up to $10^1$/s–$10^3$/s) caused by explosive and impact loadings [27–29]. However, it is still worth discussing that whether these dynamic constitutive models or the parameters are adapt to RCC material. Furthermore, it becomes essential to develop a constitutive model for RCC which can accurately describe the discreteness of dynamic behaviors.

In this regard, this paper extends previous studies and focus on the fundamental research on the dynamic compressive behavior and constitutive model of RCC material under impact loadings. The experimental procedures including specimen preparation and the feasibility of SHPB device are illustrated and verified in Section 2. Then, dynamic mechanical properties of RCC material at four strain-rate levels about 40/s, 70/s, 90/s, and 110/s are analyzed with statistics theory in Section 3, where the strain-rate sensitivity of peak strength, Young's modulus, and critical strain was measured and statistically analyzed. A statistical constitutive model of RCC is proposed and discussions are presented in Section 4. Finally, Section 5 summarizes the whole paper and highlights the future work.

## 2. Experimental procedures

### 2.1. Material and RCC mix proportions

RCC materials are made of mortar matrix, aggregates and additive. The mortar matrix is a mixture of water, cement, sand and fly ash, as shown in Table 1. The Water reducing agent (JM-II RCC) and air-entraining agent (HLAE) were also used for mixing. The water-cement ratio (w/c) was set equal to 0.50 and the fly ash content reached 60% by mass. The sand ratio was 31% by mass according to the performance of the mixture and the strength of concrete. From Table 2, the moderate heat ordinary Portland cement (OPC) of 42.5 Grade was used, having surface area of 325 $m^2$/kg and CaO content about 62.97%. The fly ash of II Grade was produced in Guizhou with fineness modulus of 19.60% and water demand ratio of 101. The artificial medium sand with an apparent density of 2680 kg/$m^3$ was selected as fine aggregate. To sum up, the physical and chemical property indexes of basic materials were met the code requirements [30,31]. Based on the code for mix design of hydraulic concrete [32], the proportion of RCC mixture adopted in this work was prepared. According to Table 3, the maximum aggregate size of RCC casted in exper-

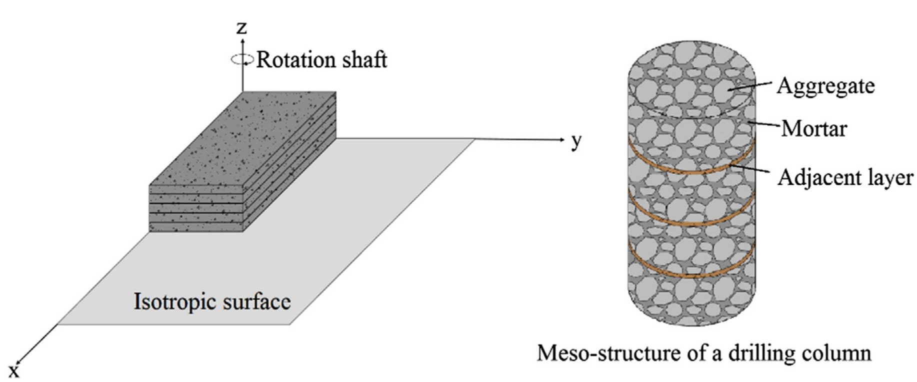


**Fig. 1.** Diagrammatic sketch of RCC structure.

**Table 1**
The mixture proportion and parameters for RCC.

| W/B | Sand ratio (%) | Fly ash content (%) | Water reducing agent (%) | Air entraining agent (%) | Material consumption (kg/$m^3$) | | | | | Air content (%) | Wet density (kg/$m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Water | Cement | Fly ash | Sand | Aggregate | | |
| 0.50 | 31 | 60 | 0.8 | 0.05 | 88 | 70 | 106 | 672 | 1507 | 3.8 | 2453 |