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Influence of calcium carbonate whisker and polyvinyl alcohol- steel hybrid fiber on ultrasonic velocity and resonant frequency of cementitious composites

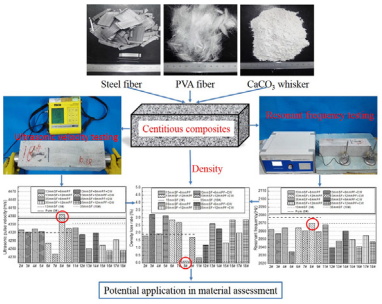
Li Li, Mingli Cao *

School of Civil Engineering, Dalian University of Technology, Dalian 116024, PR China

HIGHLIGHTS

- New cementitious composites with steel-PVA hybrid fibers and $CaCO_3$ whisker.
- Ultrasonic pulse velocity (UPV) and resonant frequency (RF) were studied.
- There exists fiber gradation in hybrid fiber reinforced cementitious composites.
- $CaCO_3$ whisker decreased ultrasonic pulse velocity and resonant frequency.
- UPV and RF have potential use in hybrid fiber reinforced cementitious composites.

GRAPHICAL ABSTRACT



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ABSTRACT

Inclusion of hybrid fiber in cementitious composites could restrict the growth of cracks at different stages and improve the mechanical properties of concrete, and adding calcium carbonate ($CaCO_3$) whisker would further improve the mechanical properties of cementitious composites. Nevertheless, no attention has been paid to the effects of steel- polyvinyl alcohol (PVA) hybrid fiber and whisker on ultrasonic pulse velocity (UPV) and resonant frequency (RF) of hybrid fiber reinforced cementitious composites (HyFRCC), although they have been used widely in quality assessment of concrete. In this research, 114 specimens have been used to explore the influences of steel-PVA hybrid fiber and whisker on the UPV, RF parameters and the mechanical properties. The results of this research present that there may exists "fiber gradation" in HyFRCC, because there is always a best fiber combination to reach the greatest compactness and highest non-destructive testing results. In addition, the partial substitution of PVA fiber by whisker decreased UPV and RF and increased density loss rate and compressive strength except for one mixture. Therefore, UPV, RF can reflect the effect of whisker on the inner structure and detect the variation, and have potential use to evaluate HyFRCC in engineering applications.

1. Introduction

The failure of cementitious composites is a progressive and multilevel process on loading, pre-existing or new born micron-cracks grow to meso-cracks and macro-cracks. Eventually, the macro-cracks lead to the fracture [1–3]. In this sense, combination of fibers with different sizes and constitutions is generally drawn into cementitious composites to restrict the growth of cracks at

* Corresponding author.
E-mail addresses: lili_henan@mail.dlut.edu.cn, lili_research@163.com (L. Li), caomingli_research@163.com (M. Cao).

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different stages in the failure process and improve its mechanical properties. Unfortunately, traditional hybrid fibers can hardly delay micro crack initiation and propagate because of the relatively large length and diameter [4,5]. Hence, micron calcium carbonate ($CaCO_3$) whisker with 20–30 μm length and 0.5–2 μm diameter has been introduced to restrict the initiation and growth of micro-cracks in cementitious composites by the authors firstly [6–9]. The literatures have shown that introducing $CaCO_3$ whisker into carbonate, polyvinyl alcohol (PVA) and steel-PVA hybrid fiber reinforced cementitious composites (HyFRCC) can improve the mechanical properties and microstructure of these cementitious composites [10–13], as well as reduce the production cost of fiber reinforced cementitious composites because of the much more cheaper price of $CaCO_3$ whisker than these fibers [12,13].

The non-destructive testing technique has been employed in the past to evaluate the quality and mechanical properties of conventional concrete, because of its simplicity and low cost compared with destructive testing [14–28]. There are many kinds of non-destructive testing techniques and two of the most commonly used are the ultrasonic pulse velocity (UPV) and the resonant frequency (RF) techniques. UPV technique is the most widely used nondestructive technique without considering the size and shape of specimens, which can be used in situ engineering expediently [17,29,30]. UPV testing estimates the quality of concrete according to the transmission speed of ultrasonic pulses in cementitious composites, which is calculated by a distance between centers of transducer faces divided by the transmission time. The unit weights, inside cracks and pores of the solid object increases the time travelled by ultrasonic pulses through it, and then smaller the UPV value. UPV depends on the constitute of cementitious composites, such as water/cement ratio, aggregate, mineral admixture and so on [14,16,22]. In addition, the introduction of various fibers would influence the UPV value in cementitious composites [14,16,18,28,31–37]. Topçu and Canbaz [20] reported that the addition of twist steel fiber and thick polypropylene fiber could increase the UPV of concrete containing fly ash. Similarly, Tsioulou et al. [33] reported that adding of steel fiber could increase the UPV of ultra-high performance fiber reinforced concrete. While Yazıcı et al. [19] showed that UPV of fiber reinforced concrete decreased with steel fiber content and aspect ratio. Yap et al. [14] have shown that both the polypropylene and nylon fibers slightly decreased UPV of oil palm shell concrete. Nik and Omran [16] presented that incorporation of certain amount of steel fiber and glass fiber could increase the UPV of concrete consisting nano-SiO_2, while polypropylene fiber would always led to a reduction of UPV of concrete consisting nano-SiO_2. Prakash et al. [34] reported that adding 8% volume fraction of hooked end steel fiber reinforced mortar reached the fastest UPV. Analogously, Kutanaei and Choobbasti [35] also presented that inclusion of 0.3% PVA fiber increased the UPV in all cemented sand, but introducing more PVA fiber decreased the UPV. Besides, there are a few researchers have studied the influence of hybrid fibers on the cementitious composites, while the research literatures on this topic are very few. Sahmaran and Yaman [32] studied the influence of hybrid 30 mm length hoked end and 6 mm length straight steel fiber on the UPV of self-compacting concrete, and reported that the UPV of this hybrid fiber reinforced concrete is between the UPV values of single 6 mm steel fiber reinforced concrete and single 30 mm steel fiber reinforced concrete. Tabatabaeian et al. [31] presented that UPV of single steel fiber reinforced high-strength self-consolidating concrete are nearly equal to that of plain concrete, but inclusion of steel-polypropylene hybrid fiber decreased the UPV significantly. There is no research about the influence of steel-PVA HyFRCC, although steel-PVA HyFRCC have been studied a lot in literatures [38–44]. Knowing that the introducing of steel, PVA fiber and $CaCO_3$ whisker will change the density and pore structure of cementitious composites [6,35,45], and then influence the UPV of cementitious composites. Hence, efforts have been made in this research to study the influence of steel-PVA hybrid fiber and $CaCO_3$ whisker on UPV of HyFRCC.

Resonant frequency (RF) technique is another non-destructive testing, which can be applied as an alternative to the UPV testing to assess the quality of cementitious composites. The specimen of cementitious composites is forced to vibrate by equipment and the driving frequency is varied until the tested specimen response achieves a last-ditch amplitude [46]. The driving frequency, which brings maximum response, is the RF of the specimen [46]. In addition, the dynamic Young's modulus of elasticity (DEM) can be calculated based on the transverse RF, mass, and size of the measured specimen [17,46]. RF and DEM can evaluate not only the microstructures but also the dynamic properties of cementitious composites [24–26]. Although the previous researches in the case of RF and DEM of fiber reinforced cementitious composites is not as abundant as that of UPV, the literatures have shown that adding various single fiber would change the RF and DEM of cementitious composites [23,25,26,47,48]. Topçu and Canbaz [20] reported that the addition of twist steel fiber and thick polypropylene fiber increased the RF of concrete containing fly ash, while thin polypropylene fiber decreased that of concrete. Giner et al. [26] presented that the carbon fiber reduced the RF and DEM of concrete containing silica fume slightly more than steel fiber. This work is intended primarily for detecting changes in the RF and DEM of cementitious composites with hybrid fiber and $CaCO_3$ whisker. Noushini et al. [25] have shown that 12 mm length PVA fiber mostly decreased the RF and DEM of concrete more significantly than that of 6 mm one, and RF and DEM decreases accompanied by the increase of fiber amount. There is no information about the influence of hybrid fiber on the RF and DEM of cementitious composites, so this research has studied the influence of steel-PVA hybrid fiber and $CaCO_3$ whisker on RF and DEM of HyFRCC to bridge the gap.

2. Research significance

Adding hybrid fiber into cementitious composites could restrict the growth of cracks at different stages in the failure process and improve the mechanical properties of hybrid fiber reinforced cementitious composites (HyFRCC), and introducing $CaCO_3$ whisker would further improve the mechanical properties of cementitious composites [10–12,45,49–55]. The non-destructive testing technique has been used in the past widely to evaluate the quality and mechanical properties of concrete, and two of the most commonly employed are the ultrasonic pulse velocity (UPV) and the resonant frequency (RF) techniques [14–27]. But to the best of authors' knowledge, there are very few accounts of UPV and RF application in HyFRCC, and no research about the influence of steel-PVA hybrid fiber and $CaCO_3$ whisker on UPV and RF of HyFRCC [28,31,32,45].In this research, the influence of various shape and volume fraction of steel and PVA fibers and $CaCO_3$ whisker on the UPV and RF parameters are studied to bridge the gap and popularize of these nondestructive testing methods in a new field. Moreover, the mechanical properties are also studied.

Several parameters are evaluated in this study: (i) four kinds of fibers with various size and volume fraction (2 kinds of steel fibers and 2 kinds of PVA fibers) and $CaCO_3$ whisker with different volume fraction are used; (ii) 4 kinds of different non-destructive testing index i.e. density, UPV, RF and DEM are employed; and (iii) 2 types of mechanical properties i.e. compressive and bending strength are studied. Total 19 groups and 114 specimens have been prepared to explore these parameters.