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Effect of a new type of high-strength lightweight foamed concrete on seismic performance of cold-formed steel shear walls

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HIGHLIGHTS

- A new type of HLFC with high bearing capacity and good thermal property is prepared.
- The effects of HLFC on seismic behavior of CFS shear wall are investigated.
- A simplified design formula is proposed to predicting shear strength of HLFC-filled CFS shear walls.

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ABSTRACT

High-strength lightweight foamed concrete (HLFC), as a new type of load-bearing structural material, was developed using suitable mix proportion and physical method in this study. Material properties of HLFC with dry density of 500 kg/m^3 and 700 kg/m^3 were studied by a series of tests. To investigate the effect of HLFC on seismic behavior of cold-formed steel (CFS) shear walls, three shear wall specimens were fabricated and tested under in-plane cycle loading. The effects of HLFC on failure mode, load-bearing capacity, ductility, stiffness degradation and energy dissipation capacity of the walls were analyzed. Test results indicated that HLFC with density grade of A05 and A07 exhibit higher compressive strength and better thermal insulation than conventional foamed concrete. Furthermore, the compressive strength and thermal insulation of HLFC meets the requirements of both the load-bearing capacity and thermal insulation property of shear walls. Moreover, the use of HLFC in CFS shear wall changes failure mode of the walls from local failure to shear failure. Due to compressive strength of HLFC, restriction effect of HLFC on steel frame and bond-slip behavior between HLFC and studs, HLFC-filled CFS shear walls are superior to conventional CFS shear wall in terms of load-bearing capacity, ductility, stiffness and energy dissipation capacity. Finally, based on shear strength of the HLFC-filled CFS shear walls, the existing formula proposed by the standard CNS 383-16 is suitable for predicting the shear strength of HLFC-filled CFS shear walls, and the differences between the experimental and calculated results were within 10%.

1. Introduction

With the promotion of low-carbon society and the application of green building, the development and application of energy-saving and environment-friendly materials become a hot topic. Foamed concrete is a type of cellular material composed of cement paste or cement mortar matrix enclosing a large number of micro- or macroscopic discrete air cells uniformly distributed in the mixture, which is classified as a lightweight concrete (density of 400–1850 kg/m^3). Compared with normal concrete, it has several advantages such as economic, environment-friendly and lightweight material with good workability and excellent performance on thermal insulation, acoustic insulation, fire resistance and shock absorption [1–4]. Thus, foamed concrete significantly improves the buildings performance, such as fire resistance, thermal and acoustic insulation [5]. However, this conventional foamed concrete was limited to being utilized as structural material, due to its low compressive strength (e.g., dry density of 500–1000 kg/m^3 with the corresponding compressive strength of only 1.0–5.0 MPa) [6]. Increasing the mechanical properties of foamed concrete is important for promoting its use in structural member.

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In recent years, many experimental investigations on mechanical properties of foamed concrete are found in the relevant literatures. It is observed that the compressive strength of foamed concrete has a direct relationship with dry density where the compressive strength decreases exponentially with a reduction in density (ranged between 200 and 1800 kg/m^3) [7–10]. In addition, the foam agent, cement type, water/cement ratio, curing method and characteristics of additional ingredients are reported to influence the mechanical property of foamed concrete [11,12]. Falliano et al. [13] conducted a series of compressive tests on the effect of the foam agents with different nature on compressive strength of foamed concrete. The test results indicated that the variability of the compressive strength was ascribed to a different stability behavior of the foams during the mixing phase with the cement paste, which was consistent with the previous studies [14,15]. And, the results demonstrated that synthetic foam agent leaded to more stable foamed concrete than the one obtained with protein foam agent. Hence, in order to improve the stability of fresh foams, the new-type high-strength lightweight foamed concrete proposed in this paper is produced by using pre-made foams generated by the synthetic foam agents.

Not only did the foam agent affects the compressive strength, but cement replacements such as silica fume (SF) and fly ash (FA) change the compressive strength of foamed concrete. A series of tests performed by Marcin [10] were carried out to investigate mechanical properties of foamed concrete mixes without fly ash and with fly ash content. The results showed that for the foamed concrete with density of 400–1400 kg/m^3, the compressive strength obtained for mixes containing fly ash (only 5% of cement) was approximately 20% lower in comparison to the specimens without fly ash. Moreover, Jones et al. [16,17] studied the performance of high-volume, ultra-low-density FA foamed concrete. The test results indicated that a high volume of FA up to 70% of cement phase had a small influence on the compressive strength of foamed concrete in the short term, but improved the long-term strength, which was consistent with the conclusions of the related literature [18,19]. However, Reisi et al. [20] conducted a series of compressive tests on SF foamed concrete with 20 mix designs, including different proportions of SF to cementations materials and different densities. The test results showed that replacement of cement with SF increases compressive strengths of SF foamed concrete compared with foamed concrete without SF. This was because that the pozzolanic effect and filling effect of SF had a marked effect on high foam concrete densities. In addition, Bing et al. [21] pointed out that polypropylene (PP) fiber increased the splitting tensile strength about 31.7% compared to non-PP fiber foamed concrete by the tensile test. Therefore, the new-type high-strength lightweight foamed concrete in this paper are produced using SF and PP fiber.

With the in-depth studies on the mechanical properties of foamed concrete, experiments performed by Chen et al. [22] confirmed that structural high-strength foamed concrete in the density range of 1000–1500 kg/m^3 with corresponding strengths of approximately 20–50 MPa was produced by using SF, PP fiber and superplasticizer. The test results also indicated that for the given foam volume content, the addition of SF and PP fiber increased the compressive strength of foamed concrete. The compressive strength increases were up to 25–45% higher than the corresponding foamed concrete without SF and PP. These conclusions mentioned above provided the direction for the research of high-strength lightweight foamed concrete in this paper. Thus, high-strength foamed concrete not only can been utilized as a void filling and insulation material [9], but also can been utilized as structural material in load-bearing systems such as walls in buildings.

Due to excellent performance and high-strength characteristics of foamed concrete, it is an ideal core material for composite structures, especially steel-concrete composite shear walls. Some experimental studies have been conducted to investigate the effect of foamed concrete on structural performance of the walls. A series of experimental studies on compressive, seismic and flexural behavior of composite walls with lightweight steel faces and foamed concrete core were performed by Othuman Mydin and Wang [23], P. Prabha et al. [24,25], Flores-Johnson and Li [4], respectively. The test results indicated that the walls exhibit high compressive, shear and flexural strength, good ductility and energy dissipation capacity, due to load-bearing capacity of foamed concrete and restraint effect of foamed concrete on the local bucking of steel sheets. This concept has been accepted in the cold-formed steel shear walls recently. Hegyi and Dunai [26] investigated the mechanical and stable behavior of foamed concrete-filled cold-formed steel (CFS) composite walls. Test results indicated that foamed concrete significantly improves the load-bearing capacity and stability performance of the walls, because the foamed concrete provides greater compressive strength and stiffness than the CFS frame.

The previous studies mainly focused on the composite sandwich walls with foamed concrete core and lightweight steel faces. However, few researches focused on the foamed concrete-filled CFS shear walls, especially seismic behavior of the walls under in-plane cyclic loading. Moreover, the foamed concrete used in the available literatures has a high density varied from 1000 to 1800 kg/m^3, which is not beneficial for thermal and acoustic insulation performance of the walls. The compressive strength of the foamed concrete with dry density of 400–1000 kg/m^3 is basically in the range from about 1.0–8.5 MPa, which is still unsuitable to structural materials for CFS shear walls. Thus, it is essential to develop a new-type high-strength lightweight foamed concrete with dry density of 500–800 kg/m^3 and with corresponding compressive strength of 3.5–7.0 MPa in this study, and then investigate the effect of the foamed concrete on seismic behavior of cold-formed steel shear walls.

Based on above analysis, high-strength lightweight foamed concrete (HLFC) with dry density of 500 kg/m^3 and 700 kg/m^3, as a new type structural foamed concrete, is reported in this study. Furthermore, this new type HLFC as structural material is applied to the CFS shear wall structure. Therefore, a new seismic-energy-saving CFS shear wall structure using HLFC and CFS frame covered with straw board is proposed, referred to as HLFC-filled CFS shear wall, as shown in Fig. 1. Due to HLFC specific advantages mentioned above, HLFC-filled CFS shear wall exhibit better thermal and acoustic insulation performance (thermal resistance of 1.92 (m^2·K)/W), higher compressive strength and smaller cross-section width compared with conventional CFS shear walls. Straw board as the shear wall component consists of the rice and wheat straws fibers, which further improves the energy-saving and thermal insulation performance of the wall. The use of HLFC and straw board contribute to meet the requirements of the thermal insulation and energy-saving performance for green buildings. Additionally, this new type wall has been successful used for constructing a two-story residential building as a demonstration project in Jiangsu province, China, as shown in Fig. 1. Compared with an ordinary concrete-filled CFS shear wall building with the same dimensions, the weight and load bearing capability of this residential building are reduced by 59.4% and 24.6%, respectively, according to Chinese standards GB 50009-2012 [27], JGJ 383-2016 [28] and JGJ 138-2001 [29]. The comparison results indicate that the application of HLFC in CFS shear wall significantly reduces the self-weight of the structural elements, and then reduces earthquake damages of the whole structural system because earthquake forces are proportional to the structural mass. Thus, the reduction of the building mass significantly minimizes the degree of risk due to the acceleration of