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Response of precast foamed concrete sandwich panels to flexural loading

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ABSTRACT

This paper presents the results of an experimental and analytical investigation of a total of six precast foamed concrete sandwich panels (PFCSPs) as one-way acting slabs tested under flexural loads. Foamed concrete of 25.73 MPa was used to produce the PFCSP concrete wythes. The results obtained from the tests have been discussed in terms of ultimate flexural strength capacity, moment-vertical deflection profile, load–strain relationship, strain variation across the slab depth, influence of aspect ratio, cracking patterns, and ultimate flexural load at failure. An analytical study of finite element analysis (FEA) as a one-way slab model was then conducted. The increase in aspect ratio (L/d) from 18.33 to 26.67 shows a reduction of 50% and 69.6% on the ultimate flexural strength capacity as obtained experimentally and in FEA models, respectively. Theoretical analyses on the extremes of fully composite and non-composite actions were also determined. The experimental results showed that cracking patterns were observed in one direction only, similar to those reported on a reinforced concrete solid slab, as well as precast concrete sandwich panels, when both concrete wythes act in a single composite manner. The experimental results were compared with FEA model data, and a significant degree of accuracy was obtained. Therefore, the PFCSP slab can serve as an alternative to the normal concrete slab system in buildings.

1. Introduction

Precast concrete sandwich panel (PCSP) was first prefabricated as a non-bearing system called "*cladding panel*," which comprised two thick internal and external concrete wythes designed as load- and non-bearing walls, respectively [1,2]. These layers were separated by insulation, such as polystyrene (PS). PCSP is commonly used to construct the outer shell of several typical buildings, such as residential, commercial, and warehouse infrastructures [1–6]. Furthermore, PCSP is vertically spanned between foundations and floors or roofs that mostly resist axial or compression loads. PCSP is formed by two concrete wythes held together by shear connectors evenly spaced along the span of the panel [2,3,6,7]. A partial cut of PCSP including the typical shear connector used is shown in Fig. 1. The structural behavior of PCSP depends on the strength and stiffness of the shear connector, but its arrangement and spacing varies on the basis of applied load, desired composite action, panel span, and the materials used to shape the shear connectors [3,8]. Therefore, the shear connector should be equipped with adequate strength to resist the loads and preserve concrete wythes as a structural unit [4]. However, no specific rules, guidelines or design codes have been reported to determine the number or arrangements of the connectors provided [6,7]. Reportedly, the bounding layer between the insulation and concrete wythes provides shear transfer, reduces its capability over time and will not maintain the strength of the shear connector over the lifespan of the panel [1–3,9]. The proper connection can present the actual structural performance of PCSP and extend its ability to maintain the insulation in place.

A continuous steel truss-shaped shear connector is reported as the most effective shear connector that achieves high composite action and allows the full transfer of shear forces by bending between wythes [8,10–13]. Moreover, the thermal behavior is dictated by the value of insulation, whereas the buckling or bending of the panel is restricted by the strength of both concrete wythes.

The percentage of PCSP composite action includes generally regarded; fully composite, semi-composite and non-composite actions [7]. A fully composite action is designed using sufficient shear connectors that can transfer the full shear between the top and bottom concrete wythes and encourages the panel to act as a solid element. The full composite usually fails either by concrete crushing or yielding of the reinforcement bars of concrete wythes without failing the shear connectors [1,2,9,14]. The non-composite section is analyzed, designed, detailed and manufactured in a factory to ensure that the wythes can act separately even without the ability to transfer longitudinal shear forces. In the general

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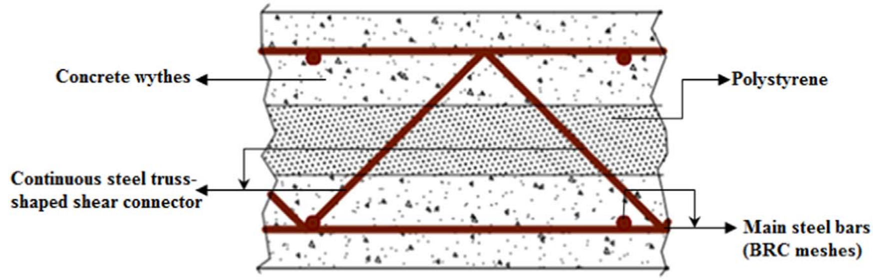

Fig. 1. A partial cut of PCSP and steel truss-shaped shear connector.

design of structural and non-structural wythes, the latter is thinner than the former. Therefore, almost 50% of shear and bending moment can be resisted [1,7,9]. A PCSP reaches its ultimate capacity when the shear connectors fail before the concrete crushing or yielding of the reinforcement bars of concrete wythes [5,15]. Therefore, the full composite, semi-composite and non-composite actions are mainly reflected in the recorded strain results, such as linear, semi-linear and non-linear across the depth of the panel, respectively [1,7,16,17]. Precast concrete insulated sandwich panels are similar to PCSP and can served as an appropriate system to construct the walls of advanced and manufactured buildings [1,15,18,19]. PCSP construction products function similar to precast solid wall panels and both differ only in their construction. Sandwich panels have become preferred materials for building elements; manufacturers are seeking sufficient viable products, whereas engineers and architects focus on structural efficiency, insulation effectiveness and energy performance of the wall sandwich panels [6,18].

However, the complex behavior of PCSP due to its material non-linearity, the uncertain design roles of the shear connector and the interaction between numerous components should be considered and verified by experimental and analytical investigations via finite element analysis (FEA). The structural behavior of sandwich panels is poorly understood because the materials used to conduct full-scale experiments are costly compared with small-scale testing models [3]. Furthermore, many sandwich panel applications in Europe and North America are proprietary; therefore, investigators and producers are strictly reluctant in sharing information with their competitors [1,2]. Moreover, construction industries are looking for viable industrial building system products manufactured using lightweight materials, such as foamed concrete (FC). FC is a cellular lightweight concrete (density of 400–1850 kg/m^3) with random air-voids created from the mixture of foaming agent in mortar [23]. FC is recognized for its high flowability, low cement content, low aggregate usage [20–23], and excellent thermal insulation [24]. Furthermore, FC is used for the fabrication of large-scale lightweight construction materials and components, such as structural components, partitioning, filling grades and road embankment infill, because of its easy production process and transfer from mobile central plants to the final position of applications [21,25,26]. In practice, FC is commonly used for constructions worldwide [27,28].

However, the first Portland cement-based FC was patented in 1923 by Axel Eriksson [29]. A further inclusive study was conducted by Valore [20,30,31]. Recently, numerous efforts have been conducted to comprehensively study the characteristics and behavior of FC to simplify its use in the structural applications for sustainable construction systems. Thus far, researchers such as Richard [23], Durack [32], Kolias. [33], Nambiar [34] and Mugahed Amran [35] reported that FC exhibits superior properties, including low density, foundation size, labor and transportation and operation costs. Furthermore, FC enhances fire resistance, thermal conductivity, and sound absorbance because of its textural surface or micro-structural cells. Another advantage of using lightweight materials in the PCSP includes the reduction of panel self-weight [23]. Few studies have been conducted using various lightweight materials to improve the quality of construction toward an industrialized building system. The existing products of PCSP are produced as heavy systems whose performance suffers in residential building constructions, particularly in soft soil or muddy ground. Moreover, studies are lacking on the structural performance of PCSP as flooring elements using a lightweight concrete material. Many engineers and designers have focused on using lightweight FC to reduce the self-weight of structural concrete applications. Mugahed Amran [36] conducted an experiment on PCSP wall applications cast by using a lightweight FC under axial loads and recommended further studies to understand the actual behavior of precast foamed concrete sandwich panels (PFCSPs) subjected to out-of-plane loads. Reportedly, the calculation of slab self-weight was shown to occupy approximately 40–60% of the total dead load of the whole structure for residential buildings [37]. Therefore, nearly 10% of the self-weight reduction in the slabs of floors may lead to a 5% reduction in the self-weight of the whole building [38]. This research aimed to develop a lightweight application called PFCSP as a slab element.

2. Experimental investigations

Six PFCSP slab specimens were subjected to flexural loads. In the experimental test, the load was applied in constant increments until failure. The cracking patterns and deformations corresponding to the load increment stages were observed, marked and recorded. All six panels had similar depths and differed only according to their span of between 2750 and 4000 mm, with 250 mm constant incremental distance between the former and subsequent specimens (Table 1). The series was chosen to investigate its feasibility as slab system element and was compared according to the behavior of the reinforced concrete solid slab principle. Moreover, the aspect ratios of all panels behaved as one-way slabs. The dimensions and details of the test panels with aspect ratios between 18.33 and 26.67 are given in Fig. 2 and Table 1. For more illustration, the difference between GF2 and GFC in Table 1 is that GF2 was cast with FC while GFC was cast with normal concrete. But, both panels (GF2 and GFC) are having similar dimensions. Hence, the aim was for comparison and validation of the actual structural behavior with a similar designed specimen (L/d = 20). The PFCSP specimens were made of two top and bottom reinforced concrete wythes that are 60 mm thick. A 30 mm-thick insulation layer of PS was present between the wythes. A welded wire mesh with 100 mm × 100 mm openings and a 6 mm diameter steel bar was used to reinforce the concrete wythes. The concrete cover was maintained at 20 mm thick to protect the wire mesh. A steel round bar with 6 mm diameter was used to shape a continuous steel truss shear connector. The top and bottom reinforced concrete wythes were integrated by continuous steel