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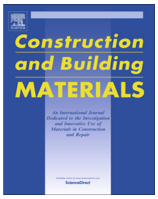

Effectiveness of foamed concrete density and locking patterns on bond strength of galvanized strip

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HIGHLIGHTS

- Compressive strength of foamed concrete is a factor of density.
- Propagation of locking holes is an effective method to increase the bond strength.
- Position of locking holes affects the load-displacement response of strips.
- An extension of holes to the upper edge of strips causes higher displacement.

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ABSTRACT

Density and compressive strength of foamed concrete as an infill material and configuration of embedded components of composite structural assemblies (CSAs) and their interaction significantly affects performance of composite panels when subjected to external loading. This paper aims to investigate the effectiveness of parameters such as density, compressive strength and locking area on bond strength of embedded components of composite panels. In order to evaluate these parameters, foamed concrete with densities ranging from 800 kg/m^3 to 1200 kg/m^3 were prepared and ten forms of locking patterns with variations in locking area and holes diameter were used as embedded parts of composite panel. The results show that increasing the density of foamed concrete results in higher bond strength and a locking system is an improper technique for foamed concrete with a density lower than 1000 kg/m^3.

1. Introduction

Behaviour of a sandwich panel and its behaviour when subjected to external loading significantly depends on infill material characteristic and its interaction with embedded components [1]. The interaction of composite systems and their behaviour rely on a wide range of effective factors which directly affect the bond strength and stability of composite panels [2]. It has been confirmed that the bond strength mostly depends on the summation of resisting shear stress which is governed by chemical adhesion, friction and mechanical interlocking at the interface of the contact area [3–5]. The resisting bond stress is mostly relying on surface friction (up to 35%) and mechanical interlocking between ribs and adjacent concrete keys [6], while the resisting stress is governed by chemical adhesion and breaks down at very small displacements of embedded components and surrounded concrete (at about 0.48–1.03 MPa) [7]. The value of resisting stress is also affected by further factors such as concrete strength [8–12], steel strength, concrete cover thickness [13], transverse reinforcement, bar spacing [14], bar size [3], bar features [14–17], yield strength of embedded bar [18,19] bar casting position [20,21], confinement [22–25] and elastic and inelastic segment [4,5]. Mechanical properties of concrete affect the magnitude of bond stress as the propagation of micro cracks and transferring the shear force largely depends on the mechanical behaviour of concrete [9] and increasing the compressive strength causes larger resisting force to develop over the length of embedded components [10]. Several equations are suggested by researchers to assess the bond stress at yield and ultimate stage [26]. The root square of concrete strength, $\sqrt{f'_c}$ is considered as the average bond stress of concrete with strength of lower than 55 MPa [27], while the bond stress of unconfined and confined concrete with greater than 55 MPa is calculated by $f_c^{1/4}$ and $f_c^{3/4}$, respectively [8,12]. The factors such as embedded bar geometry [14], rib bearing area [16,17], and rib face

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angle [16] has been studied by several researchers to investigate the effectiveness of locking components of steel bars. They concluded that the geometry of locking components (rib) and rib angle changed the behaviour of embedded steel bar as a reduction in rib face angle causes lower bond strength along with less concrete crushing at the interaction zone [18]. Confinement and confinement pressure considered as another method to enhance the bond strength of spliced bars and to eliminate the spread of splitting cracks [4,5]. Methods such as transverse reinforcement [28], spiral reinforcement [29,30], shear bolts [4], aluminium tube [31,32], steel pipe [33,34], square hollow section [35], and fibre reinforced polymer (FRP) [5] were used to provide additional confinement pressure at the splice region of reinforced concrete components.

Lightweight concrete mostly is used as infill materials in sandwich panels due to lower unit weight and lower thermal conductivity value. Substituting of conventional aggregate (normal aggregate) with lightweight aggregate such as oil palm shell [36], pumice [37,38], perlite [39,40], expended clay [41] and vermiculite [42] or foamed concrete [43] are conventional ways to produce lightweight concrete. However, mix design of foamed concrete with its advantages directly depends on foam agent specification, foam preparation method, material characteristics, mix design method, and foam concrete production [44]. Researchers used mineral admixtures such as fly ash [45], ground granulated blast furnace slag [46,47], silica fume [47] to increase matrix consistency and strength. In order to reduce the unit weight foamed concrete, lightweight aggregates such as lime [48], oil palm shell [49], fly ash [50], chalk [51], crushed concrete [51], expanded polystyrene [52], Lytag fines, foundry sand [53] and quarry finer [53] were used. ASTM C 796-97 [54] provide a method for calculation of foamed volume with known water-cement ratio and density, while Kearsely and Mostert [45] proposed an equation based on mixture composition for estimating the foam volume and cement content.

To overcome the lack of knowledge on interaction between infill materials and embedded parts of sandwich panels and to provide new information on locking systems and its effects on bond strength of embedded region, ninety specimens with variation on foamed concrete density, compressive strength, locking patterns, locking area, holes diameter and locking length were prepared and tested under direct tensile load.

Table 1
Chemical compositions of cement and fly ash.

Materials	Composite (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2
Cement	22.8	4.2	2.3	64.8	1.0	0.19	0.49	0.42	–
Fly ash	40.1	20.4	10.1	19	3.4	2.1	0.5	0.8	1.5

Table 2
Mix proportion of preformed aqueous foam.

	Water (Litres)	QUICK-GEL viscosifier (kg)	QUICK-FOAM foaming agent (% by volume)
Mud-Mist Foam	1000	30	0.3–1.0

2. Experimental study

2.1. Materials

2.1.1. Cement and fly ash

A locally available Portland cement (Type GP) accordance with NZS3122:2009 [55] and fly ash class C from Golden Bay Cement Company were used as binding materials for foamed concrete. The fly ash was substituted with 33% of cement weight to improve more uniform distribution of voids by preventing merging of bubbles in the matrix. The chemical compositions of cement and fly ash are shown in Table 1.

2.1.2. Foaming agent and viscosifier

In order to provide stable foam for lightweight foamed concrete, a high performance foaming agent (Ultra-Foam) along with a specific viscosifier (QUICK-GEL) from Baroid IDP were used as main components of foam. The mix proportion of water, foaming agent and viscosifier are shown in Table 2.

2.1.3. Galvanized steel

A hot-dip galvanized strip (G250) with thickness of 0.75 mm were prepared from GALVSTEEL of New Zealand Steel with yield, f_y and ultimate, f_u strength of 250 MPa and 320 MPa, respectively.

2.2. Specimens preparation

2.2.1. Foamed concrete

Preparation of foamed concrete needs special consideration as the lower water-binder ratio results in a too stiff mix and causes air bubbles breaks during mixing, while a higher water-binder ratio makes the mixture too thin to hold the air bubbles and causes mixture segregation along with higher density. In order to achieve target densities along with stable mixture, Kearsley and Mostert's equation [45] and the absolute volume method were used to calculate the mix proportion of foamed concrete. A high performance foaming agent (ULTRA-FOAM) with specific gravity of 1.03 was used and diluted in water with a ratio of 1:47 (foaming agent: water). In addition, a viscosifier (QUICK-GEL) was mixed with water prior to diluting with foaming agent with a ratio of 1:34 (Quick-Gel, kg: Water, litre) to improve hole-cleaning capability and to reach the maximum viscosity. The foaming agent, viscosifier and water were poured into to foam generator (compressed air of generator was kept at 517 kN/m^2) to produce stiff foam with a density of 56 kg/m^3. Then, the required amount of foam was added to the base mortar (cement-fly ash) and blended by a rotary drum mixer until a uniform mixture was obtained (about 2 min). The water–cement ratio and water–binder (cement + ash) ratios were considered 0.5 and 0.33 for all samples, respectively. In total, three mixes of foamed concrete were prepared with densities of 800, 1000 and 1200 kg/m^3 and were labelled FC8, FC10 and FC12, respectively. The mix proportions and densities of the foamed concrete are shown in Table 3.

2.2.2. Embedded strip

In total, ten types of strip patterns with variations in holes pattern, holes diameter and holes area were proposed and prepared to evaluate the effectiveness of locking area and strip configurations on bond strength and tensile capacity. The strips samples were labelled by number of holes (N) and holes radius (R). The specifications of strips are illustrated in Table 4 and Fig. 1.

2.3. Test method

2.3.1. Compressive strength test

The compressive strength of foamed concrete was carried out on 100 × 200 mm (diameter × height) standard cylinders in accordance with ASTM C39 [56] (Test method for compressive strength of cylindrical concrete specimens) as the unit weight of proposed foamed concrete is higher than 800 kg/m^3. The cylinders were cast in standard steel moulds and demoulded after 24 ± 2 h. The specimens were kept in water curing at 20 °C for the whole curing period and then oven dried at 110 ± 5 °C for 24 h a day before the scheduled date of test (28 days). The average results of three specimens were considered as compressive strength of foamed concrete (Table 3).

Table 3
Mix proportions of foamed concrete.

Specimens	Target density (kg/m^3)	Average actual density (kg/m^3)	Foam content (kg/m^3)	Water content (kg/m^3)	Cement content (kg/m^3)	Fly ash content (kg/m^3)
FC8	800	848.0	33.6	191.4	382.9	191.4
FC10	1000	1049.8	32.7	242.9	485.9	242.9
FC12	1200	1260.4	21.5	294.5	589.0	294.5