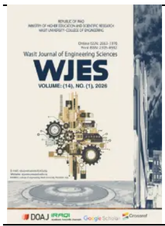

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Original Research

Effects of Bottom Layer and Insulation Thickness on Mechanical Behavior of Precast Concrete Sandwich Panels

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ABSTRACT

Precast Concrete Sandwich Panels (PCSP) are lightweight structural elements that are composed of two thin outer concrete wythes and a middle insulation core. This article presents an experimental work that investigates the effect of the thicknesses of the bottom wythe and the insulation core on the flexural response of six PCSP specimens. Two parameters were adopted in the study, which are the lower wythe thickness and the core thickness. Three lower wythe thicknesses of 10, 15, and 20 mm, in addition to two core thicknesses of 50 and 100 mm, were considered. Therefore, six PCSPs were cast and tested under four-point loading. The load and corresponding deflection were simultaneously recorded using the data logger of the displacement-controlled testing machine. A constant self-compacting concrete mixture was used for all specimens. The test results showed a positive impact of bottom wythe thickness and insulation core thickness on the ultimate load capacity of the tested PCSPs, where percentage improvements reaching approximately 16% and 29% were recorded as the wythe thickness increased from 10 mm to 15 mm and 20 mm, respectively. However, a lesser percentage increases within a maximum of 12% were retained by increasing the core thickness from 50 to 100 mm. In addition, the 50 mm core PCSPs exhibited a more uniform flexural cracking pattern compared to those with a 100 mm core.

Keywords: Precast concrete sandwich panels (PCSP); insulation core; flexural behavior; wythe thickness; deflection.

1. Introduction

Precast Concrete Sandwich Panels (PCSP) are a construction solution that combines acceptable mechanical strength with good thermal properties. This system usually consists of two, top and bottom, cementitious or concrete layers (wythes), separated by an insulating middle layer of light thermal-insulation material such as expanded polystyrene (EPS). The wythes are typically linked by metal connectors (shear connectors) that assure a type of composite action within the plate system. In many structural applications, this system is chosen owing to its many advantages that include moderately low cost, ease of construction, and short construction period compared to conventional reinforced concrete, in addition to its preferred thermal insulation properties that afford a cost-effective energy-saving alternative where air conditioning is an essential requirement. However, the low load-bearing capacity of PCSP makes it more suitable for use as a roofing alternative than as a sustainable floor. Thus, compared to conventional roofing materials that use larger quantities of steel and concrete, PCSP can be considered a greener and more environmentally friendly roofing solution for many applications.

Several previous studies attempted to explore the mechanical properties of PCSP units. Christadoss et al [1] conducted an innovative small-scale concrete sandwich panel specimens with a previous concrete core. The conclusions showed that previous concrete can be used as a core in concrete sandwich panels. Truss-shaped shear connectors are required to achieve the composite action of the sandwich panels with the pervious concrete core. Bonding action at a wythe-to-core interface cannot be relied upon. Increased thickness of the core and increased number of shear connector links provided higher ultimate strength of the panels. Chen et al. [2] used a rigid foam insulation layer with shear connectors made from fiber-reinforced polymers and ensured their noticeable mechanical bond activity in addition to their ability to reduce thermal bridging. Amran et al. [3] investigated the flexural performance of precast foamed PCSPs using truss-shaped shear connectors, which showed a high degree of composite action that afforded a full-composite action under flexural loading. Tomlinson et al. [4] evaluated the flexural behavior of PCSPs using steel and basalt fiber reinforced polymer connectors, which revealed lower thermal bridging than steel connectors, but exhibited lower composite action compared to steel.

In general, all the above studies confirmed the positive effect of increasing the thickness of the bottom wythe to improve the flexural capacity and stiffness of PCSPs. Despite that, Li et al. [5] confirmed this result; they reported noticeable reductions in ductility with the increase of the bottom wythe thickness. Joseph et al. [6] indicate that the truss-shaped shear connectors are effective in achieving composite action of the panels until failure. Test results also indicate that the panel thickness affects the flexural load-carrying capacity, and the size of the wire mesh affects the ductility. Segura-Castillo et al. [7] found that it was possible to optimize panel reinforcement and geometry, thereby reducing wythe thickness. Besides the reduction in production time, it was possible to achieve cost savings of up to 10% by replacing steel mesh with fibers and of more than 20% if the geometry was also modified. O'Hegarty et al. [8] found that increasing the lower wythe thickness in PCSP panels from 25 mm to 40 mm significantly improved the flexural stiffness, load-bearing capacity, ultimate strength, and ductility, which disagrees with Li et al. [5] conclusions about ductility. Other studies, like Lee et al. [9] and Tawil et al. [10] studied the effect of the insulation material in addition to the geometry properties of the PCSP panels.

As it is disclosed in the previous paragraphs and the reviewed literature, precast concrete sandwich panels can be used as a preferred cost-effective, environment-friendly roofing system for many structural applications, including small and medium industry areas, low-cost warehouses, office and residential areas of temporary work camps, and rural low-cost single-story residential units. The reviewed literature showed that although there is a kind of agreement about the effect of the bottom wythe thickness on the strength capacity of PCSPs, there are still some disagreements about some properties, like ductility and the dual effect of wythe thickness and insulation thickness on their flexural behavior. Therefore, aiming to help partially fill this gap and add more experimental results to the literature, an experimental program was conducted in this study to investigate the dual effect of bottom wythe thickness and insulation layer thickness by conducting flexural tests on six PCSP roofing panels.

2. Experimental Work

2.1 Mix design

After many trials to achieve an adequate self-compacting concrete mixture, a final mixture was adopted to construct the PCSP specimens and their control cube specimens. This mixture includes 500 kg/m^3 cement, 850 kg/m^3 sand, a water/cement ratio of 0.35, and 1.0 % superplasticizer by cement weight. The mixture gave the required self-compacting properties that align with the requirements of EFNARC [11]. The basic self-compacting fresh-properties tests showed that the slump was 770 mm, the T_{50} was 2 seconds, and the J-ring flow difference was (770 – 760 = 10 mm). The cement used was local ordinary Portland cement type R42.5, while the sand was local river sand from the eastern region of Wasit province with a maximum particle size of 2.35 mm.

2.2 Experimental panels and test setup

The experimental PCSP specimens were made using EPS insulation with two different thicknesses of 50 mm and 100 mm. Table 1 shows the physical and chemical properties of the EPS core material used between the concrete wythes. Three different bottom wythe thicknesses of 10, 15, and 20 mm were considered to evaluate the effect of the bottom wythe's thickness, while the thickness of the top wythe was 10 mm for all panels. Steel meshes with 1.67 mm diameter wires and 32 mm equal spacing in both directions were used as a reinforcement for the bottom wythe. On the other hand, the top wythe was reinforced using a fine wire mesh with 0.5 mm diameter and 12.5 mm openings. On the other hand, 3 mm diameter hooked steel wires with 60 mm top and bottom hooks along the span direction were utilized to connect the top and bottom wythes. Table 2 lists the details of the six PCSP specimens, while Figure 1 shows their configuration. Table 3 presents the mechanical properties of mesh wires. Figure 2 shows the reinforcement of the bottom wythe and the making process of the panels. All of the six panels were cast in one patch, with which a set of 150 mm concrete cubes was cast to evaluate the compressive strength of the used cementitious mixture. The specimens and cubes were all tested at an age of 7 days.

Four-point bending tests were conducted using a displacement-control testing machine to explore the full details of the load-deflection curves. The specimens were tested over a simple span of 800 mm, while the shear spans were 267 mm each. The applied load and the central deflection were recorded simultaneously using the data logger of the test machine, which records and draws the load-deflection curve with time.

Table 1. Physical and chemical properties of the EPS core material

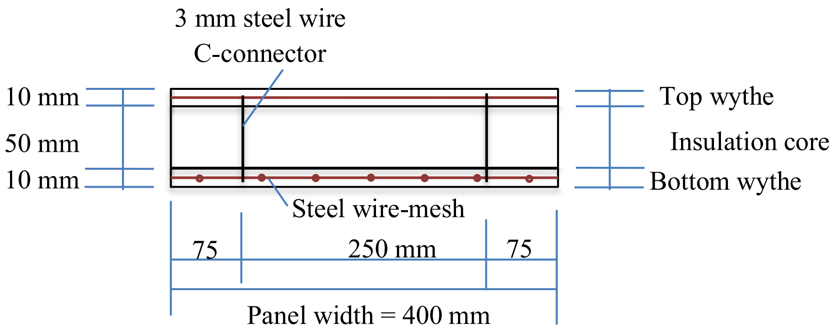
Property	Specification / Description
Material Type	Expanded Polystyrene (EPS)
Apparent Density	12 kg/m³
Thermal Conductivity (λ)	0.040 - 0.043 W/m·K
Compressive Strength (at 10% deformation)	60 kPa
Water Absorption	7 %
Softening Point	90 °C
Chemical Stability	Does not react with acids, salts, or alkalis
Behavior in alkaline environment (cement mortar)	Stable – does not chemically degrade or interact with high-pH cementitious media (pH 12–13)
Decomposition risk	No decomposition under normal concrete curing conditions

Table 2. Properties of the six experimental PCSP specimens

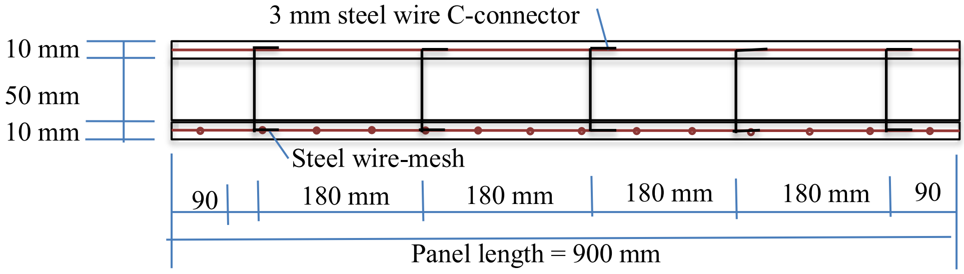
Plate ID	Thickness of top wythe (mm)	Thickness of bottom wythe (mm)	Insulation thickness (mm)	Wythe reinforcement	F_{cu} (MPa)
S1	10	10	50	Ø1.67 mm @32×32 mm	50.73
S2		15	50		
S3		20	50		
S4		10	100		
S5		15	100		
S6		20	100		

Table 3. Mechanical properties of mesh wires

Reinforcement Type	Wire Diameter (mm)	f_y (MPa)	F_u (MPa)	Maximum Elongation (mm)
Bottom Wire Mesh	1.67	531	570	2.77 %
Shear Connector	3	322	388	2.65 %



(a) Lateral cross-section



(b) Longitudinal cross-section

Figure 1. Configuration and reinforcement details of the experimental PCSP specimens

(a) (b)

(c) (d)

Figure 2. Production of the PCSP specimens (a) reinforcement of bottom wythe (b) casting of bottom wythe (c) placing of insulation core, reinforcement of top wythe and shear connectors (d) casting of top wythe

3. Results & Discussion

3.1 Cracking and ultimate loads

The experimental investigation assessed the mechanical behavior of experimental PCSP specimens incorporating varying bottom wythe thicknesses (10, 15, and 20 mm) combined with the thickness of the insulation core (50 and 100 mm). The primary experimental records were the ultimate load capacity and the corresponding deflection, together with the maximum displacement and its corresponding load. The term "ultimate load" in this study refers to the maximum recorded load along the full length of the load-deflection curve, as listed in the third column of Table 4, which is absolutely associated with a deflection record that is presented in the fourth column of Table 4. On the other hand, the failure point of the beam where the recording of test data is stopped records the maximum deflection of the tested beam, as tabulated in the sixth column of Table 4. The load associated with the maximum deflection is given in the fifth column of Table 4, which is typically less than the ultimate load due to the strain softening under excessive cracking before failure. The maximum deflection records were added to give a picture of the plastic deformation range of the specimens, which gives an idea about the toughness and ductility of the specimens.

Results indicate that increasing the bottom concrete wythe thickness generally enhanced the ultimate load-bearing capacity of the PCSP specimens. For instance, specimens with 20 mm bottom wythe exhibited higher maximum loads compared to those with 10 mm and 15 mm thicknesses under the same insulation conditions. As listed in Table 4 and shown in Figure 3, for specimens with a 50 mm thick insulation core, the increase of the bottom wythe thickness from 10 mm to 15 and 20 mm increased the ultimate load from 2.88 kN to 3.33 and 3.72 kN, respectively. This means that increasing the thickness from 10 to 15 and 20 mm led to percentage increases in load capacity of 15.6% and 29.2%, respectively. On the other hand, the similar sequence of percentage increases in ultimate load capacity for specimens with 100 mm insulation core was 15.8% and 18% as the thickness increased from 10 to 15 and 20 mm, respectively. This improvement can be attributed to the increased cross-sectional stiffness and higher contribution of the thicker concrete wythe to overall panel strength. This result aligns with the findings of previous studies [12,13]. Waryosh et al. [14] reported a 41% increase in percentage when the thickness of the bottom wythe increased from 10 mm to 20 mm.

Regarding the thickness of the insulation core, increasing the thickness from 50 mm to 100 mm exhibited a slight reduction in load-bearing capacity. This reduction is due to the larger volume of low-strength material within the panel cross-section, which decreases the structural contribution of the core. However, the impact of insulation thickness was less significant compared to the influence of the bottom layer thickness. Table 4 and Figure 4 show that increasing the insulation core thickness from 50 mm to 100 mm led to percentage improvements in ultimate load capacity of specimens with 10 mm bottom wythe thickness by 11.8%, while for specimens with 15 mm bottom wythe, the percentage increases was 12%, and for specimen with 20 mm bottom wythe, the percentage increase was only 2.2%.

Table 4. Test results for the specimens tested for loading and deflection.

No.	Sample	Ultimate Load Records		Maximum Deflection Records	
		Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
1	S1	2.88	18.2	2.65	25.8
2	S2	3.33	12.7	2.787	21.8
3	S3	3.72	15.5	3.212	21.0
4	S4	3.22	22.7	2.57	27.8
5	S5	3.73	23.0	3.58	28.8
6	S6	3.80	21.4	2.93	29.7

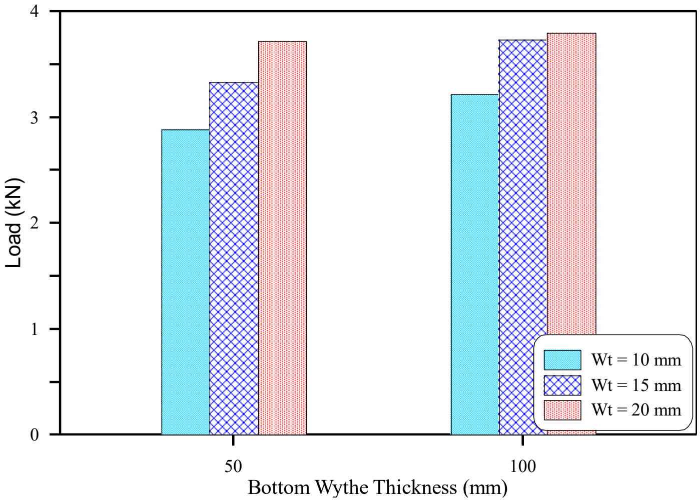


Figure 3. The bottom wythe effect on load capacity

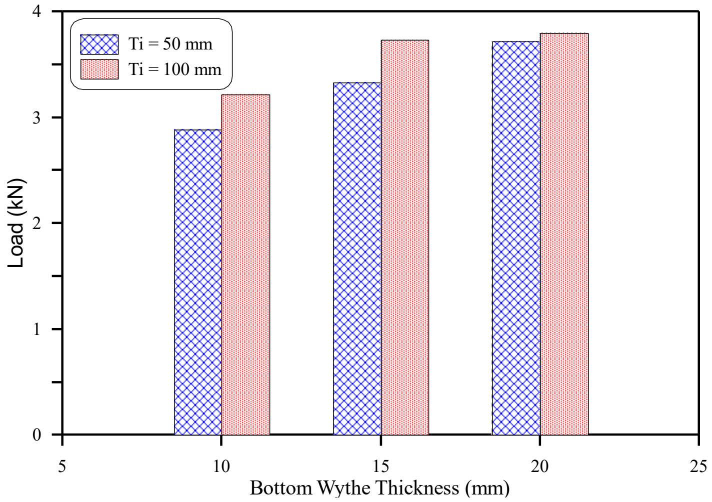


Figure 4. The effect of insulation thickness on load capacity

3.2 Load-deflection relations

The results showed that S4, S5, and S6 exhibited larger ultimate deflections of 27.75, 28.76, and 29.72 mm, respectively, versus 25.78, 21.76, and 27.95 mm for S1, S2, and S3, reflecting the greater deformation capacity of the specimens with a 100 mm core compared to those with a 50 mm core. Amran et al. [3], Li et al. [5], and Alev et al. [6] showed a similar trend of results. Figures 5 to 7 show comparisons between the load-deflection curves of identical specimens (same wythe thickness) but with different isolation core thicknesses (50 and 100 mm). From the flexural ductility standpoint, S4, S5, and S6 maintained a more gradual decline in load beyond the peak point and exhibited a broader post-peak deflection range, suggesting superior energy dissipation and ductility. Collectively, these results indicate that S4, S5, and S6 possessed a more favorable load-bearing and deformation profile, rendering them more effective under flexural loading conditions. Figure 8 compares the load-deflection curves of the three specimens S1, S2, and S3 with an insulation thickness of 50 mm but with different wythe thicknesses, while Figure 10 compares the same relations for the specimens S4, S5, and S6 with a 100 mm insulation thickness. The experimental analysis of the load–deflection response of the three PCSP specimens (S1, S2, and S3) and (S4, S5, and S6) revealed a consistent improvement in structural performance with increasing bottom concrete layer thickness. Specifically, specimens S3 and S6, which included a 20 mm bottom wythe, achieved the highest ultimate loads (3.7 and 3.8 kN), and exhibited the greatest ductility, which is indicated by the deflections that exceeded 27 and 29.7 mm, respectively. Moreover, the post-peak behavior was characterized by a gradual decline, suggesting improved toughness and energy dissipation capacity. These observations align with previous results emphasizing the structural benefits of increasing concrete thickness in PCSPs, such as the conclusions of Li et al. [5], who reported notable gains in the cracking load, ultimate strength, and flexural stiffness of the panel system upon increasing the thickness of the bottom wythe.

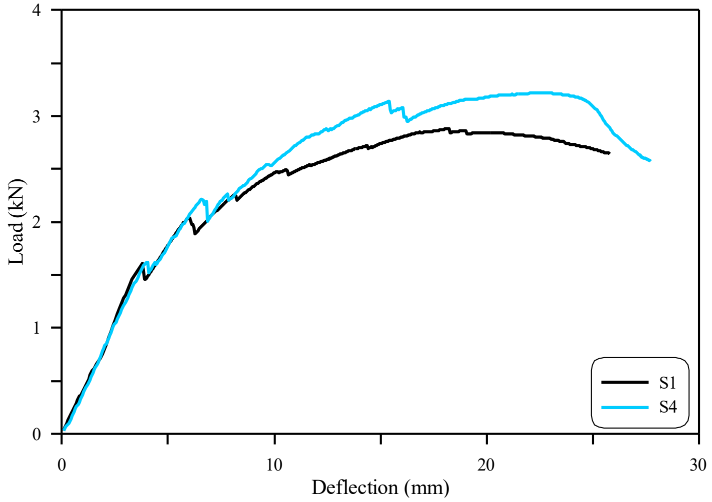


Figure 5. Load-deflection of specimens S1 and S4

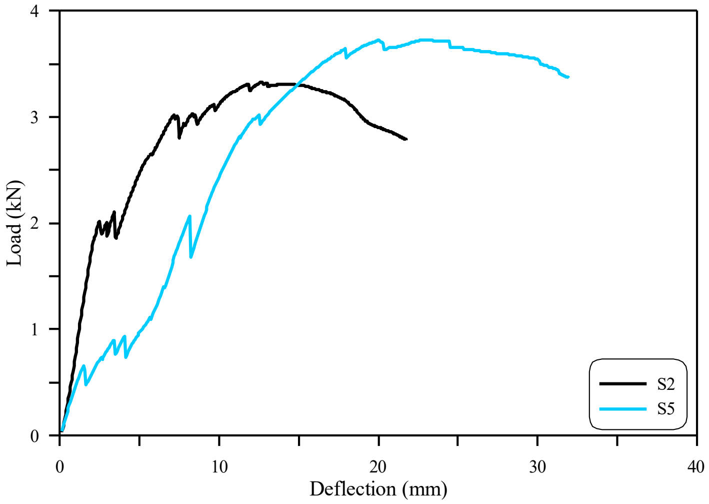


Figure 6. Load-deflection of specimens S2 and S5

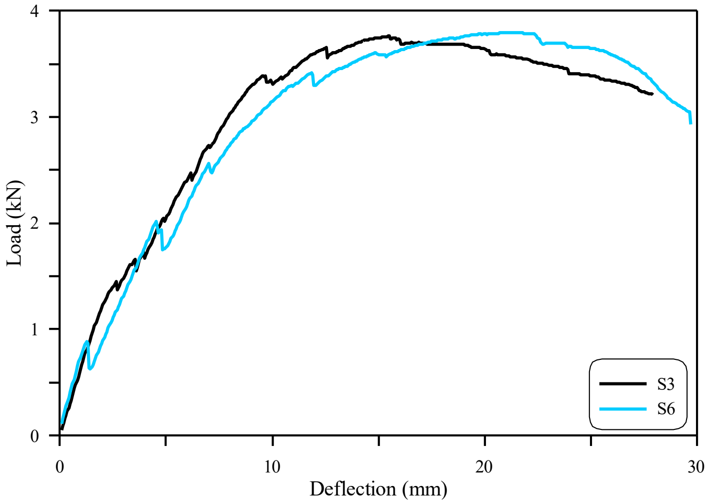


Figure 7. Load-deflection of specimens S3 and S6

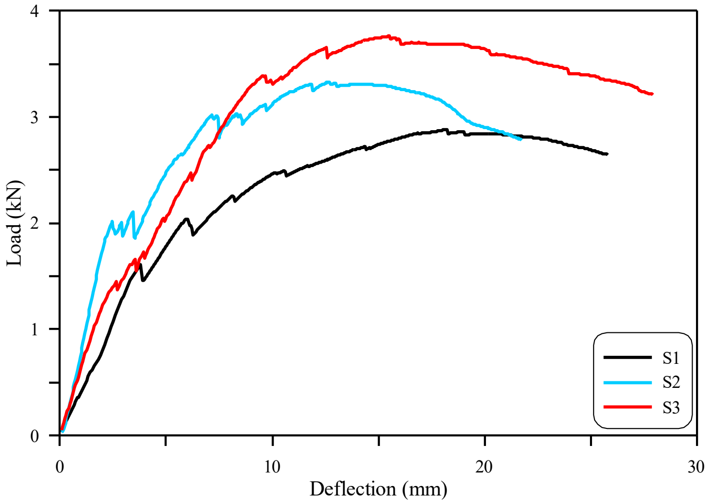


Figure 8. Load-deflection of specimens S1, S2, and S3

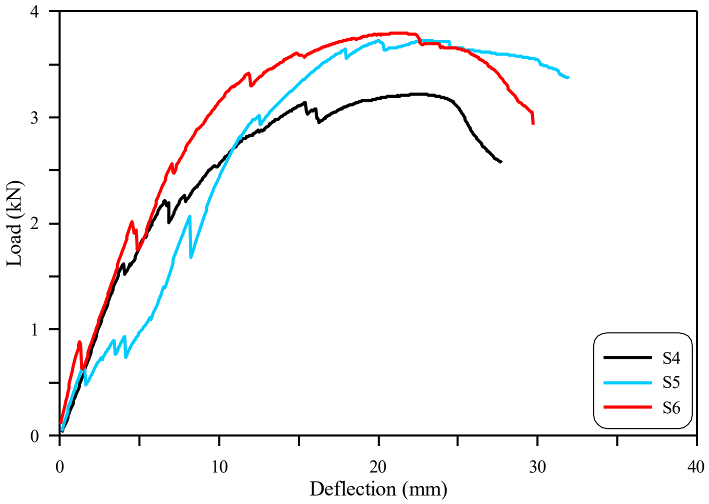
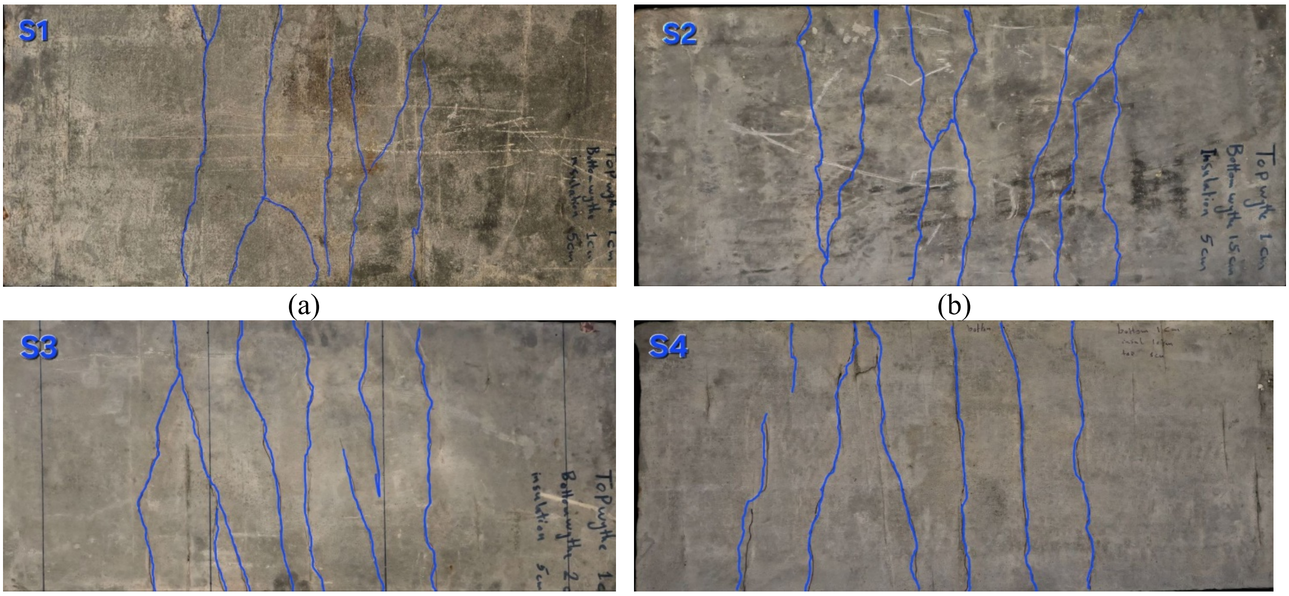


Figure 9. Load-deflection of specimens S1, S2, and S3

3.3 Cracking and failure patterns

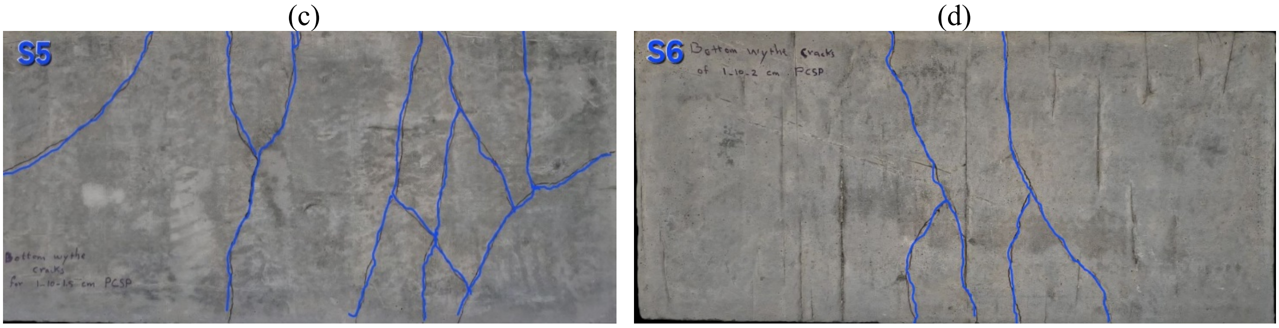
Figure 10 shows the ultimate (after failure) cracking patterns of the tested specimens. A general observation is that all specimens exhibited fine cracking at the bottom surface of the bottom wythe, where the crack width was, in general, within a maximum limit of 1 mm. This behavior is attributed to the fine materials of the mixture in addition to the fine and closely spaced wire reinforcement. However, the number of cracks and their alignment were not the same for all specimens. On the other hand, the top surface exhibited minor longitudinal compressive cracking beneath load lines, which became more obvious before failure. The specimens S1, S2, and S3 with the smaller insulation thickness (50 mm) exhibited an almost identical ductile cracking pattern with multiple thin lateral (almost vertical to span direction) cracks, as shown in Figures 11(a), (b), and (c), revealing a favorable ductile response. This means that within the limit of the used insulation thickness, increasing the thickness of the bottom wythe has a minimal influence on the flexural cracking behavior. The same stands for specimen S4, which has a 100 mm core and 10 mm wythe as shown in Figure 11(d), which also exhibited the trend of multiple, thin, lateral cracking. On the other hand, the specimen S6 (Figure 11(f)) with the combined thickest bottom wythe (20 mm) and thickest core (100 mm) exhibited a less ductile behavior with a smaller number of cracks. This behavior might be attributed to the lower composite action that led to less stress transfer from the top surface to the bottom wythe, leading to a more brittle response. On the other hand, the specimen S5 (Figure 11(e)) exhibited a transition behavior between the behaviors of specimens S1 to S4 and that of specimen S6, which is attributed to the same above reasons due to its thicker wythe thickness (15 mm) combined with its thick core (100mm). It should be mentioned that specimens S1 to S4 didn't show visible wythe-core separation, while such separation was noted at the failure stage for specimens S5 and S6.



(a)

(b)

(c) (d)



(e) (f)

Figure 10. Cracking patterns at failure of test specimens (a) Specimen S1 (b) Specimen S2 (c) Specimen S3 (d) Specimen S4 (e) Specimen S5 (f) Specimen S6

4. Conclusions

An experimental work on precast concrete sandwich panels reinforced with steel wires was conducted in this study to investigate the effect of the thickness of the bottom wythe and insulation core. Six plate specimens were tested under four-point bending, where displacement-controlled loads and deflections were recorded simultaneously. The most important conclusions from the experimental plates are listed below.

1. Increasing the bottom wythe thickness significantly enhanced both the ultimate load capacity, leading to improved structural performance. The results showed that increasing the thickness of the bottom wythe from 10 to 15 mm increased the ultimate loads by up to 15.6 %, while for specimens with a 20 mm thick bottom wythe, the ultimate loads increased by up to 29.2%.
2. Increasing the thickness of the insulation core also has a positive impact on the ultimate load capacity, where for specimens having the same wythe thickness, increasing the insulation core thickness from 50 to 100 mm increased the ultimate load capacity by approximately 2 to 12%.
3. The load-deflection curves showed that specimens with a thicker bottom layer mostly exhibited higher initial stiffness, where the thicker bottom wythe specimens S3 and S6 showed smaller deflections along the elastic part of the curve compared to specimens S1 and S4 with 10 mm bottom wythe thickness.
4. In general, all specimens exhibited fine cracking, where crack widths were within the limit of 1 mm. The specimens with 50 mm insulation thickness exhibited a better cracking pattern with a more uniform and larger number of lateral continuous flexural cracks compared to those with a 100 mm thick insulation core.
5. Despite its significant effect on ultimate load capacity, the results showed that the thickness of the bottom wythe has minimal effect on cracking pattern, where the 50 mm-core specimens S1, S2, and S3, having 10, 15, and 20 mm, exhibited the same cracking pattern with almost the same number of cracks and crack spacing.

Declaration of Competing Interest

The authors confirm that there are no conflicts of interest regarding this article and the related research work.

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Author Contributions

Omar M. H. Chlaibawi: Methodology; Investigation; Resources; Writing-original draft preparation; data analysis
Sallal R. Abid: Project administration; Conceptualization; Formal analysis; Data curation; Supervision; Writing-review and editing

Mustafa Özakça: Writing-review and editing; validation; software
Khaldoon S. A. Altameemi: Methodology; Resources; data analysis

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