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Civil Engineering Journal

Vol. 6, No. 9, September, 2020

Effect of Changing Properties of Wythes in Precast Structural Sandwich Panels

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Received 08 May 2020; Accepted 03 August 2020

Abstract

This study investigates the effects of changing in the properties of face and core wythes in structural sandwich panels (with dimensions of 500×500 mm and 120 mm total height). Concrete face wythes of three grades (80, 70, 37) MPa, thicknesses of (25, 35, and 45) mm, and three types of core materials (high density foam, polyethylene foam, and palm bark) were used in the production of panels. Steel shear connectors were installed in the panels with angle of 45º. Three-point bending load test was carried out on all panels and results were compared with both of the theoretical extremes capacities of non- composite and fully-composite states and ANSYS software results. The degree of composite action (%) and the (strength/weight) ratio were the main parameters that judged the specimens. It was found that upgrading concrete increased overall strength of slabs especially in high strength concrete (80 MPa), however the use of lightweight concrete (70 MPa) caused high (strength/weight) ratio due to very lightweight. Results revealed that decreasing thickness of concrete face wythes had a positive effect on strength/weight ratio (although the ultimate loads decreased) that enhanced the performance of panels as lightweight structural panels. The optimum face wythe thickness is that of 2.5 cm and has high (strength/weight) ratio. It was noticed that adding polyethylene foam as a core material results in positive effect and high (strength/weight) ratio. Results revealed that high strength concrete (80 MPa) and light-weight concrete (37 MPa) are very successful in the production face wythes of precast light-weight sandwich panels that can obtain high (strength/weight) ratio and high percent of composite action.

Keywords: Sandwich Panel; Composite; Light-Weight; Strength\Weight; Insulation Core.

1. Introduction

The common typical cross section of structural precast sandwich panel (SPSP) consists of two face wythes of concrete separated by core wythe that almost consists of heat insulation material [1]. Various parameters control the structural behaviour and the overall ultimate capacity of structural precast sandwich panels such as the grade of concrete in concrete face wythes, thickness of concrete face wythes, distribution of shear connectors, rigidity of core material, and bond between core-concrete interfaces [1, 2]. It was found that shear flow capacity tends to decrease with the increase of core wythe [1]. Previously, ultra-high performance concrete was successfully the production of face wythes of SPSP with the core material of high performance expanded polystyrene. The panels were classified as light weighted high-strength structural sandwich panel [2]. The relative light weight comparing to high strength is playing the main role which controls the performance of SPSP [2, 4].

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http://dx.doi.org/10.28991/cej-2020-03091581

Many types of insulation materials were tested as core materials in SPSP. It was found that expanded polystyrene foam was very successful at service load level [3]. It also was found that high density foam is very practical, rigid, and light-weight when it was used as the core material in SPSP [14, 16]. There is more than material to be used as shear connectors in SPSPS such as steel, carbon fiber, and basalt fiber reinforcement polymers (BFRP) that can play this effectively [4, 5], however the composite action obtained with BFRP was less than that one with steel shear connectors [5]. Generally, it was found that fiber reinforced polymers are successful to be used in structural sandwich panels as main steel and shear connectors due to its increased deflection and deformability [5, 6]. The increases of the number of shear connectors was found to increase the overall ultimate capacity of panels [4, 6, 16]. Sudden failure was observed in four-point loading system test due to the Combination of flexural and shear stresses [5, 7]. It was previously found that the lightweight in sandwich panels gave opposite advantages in overall capacity loading [8, 13].

It was noticed also that the overall deflection of sandwich panels depends on the shear deformation of the core layer, material, and its thickness [5, 9]. It was found also that the truss-shaped connectors made of wires were successful to achieve composite action [10]. The continuous-type connectors can structurally behave better than stud-type connectors [11]. In general, also it was noticed that larger deformation was observed due to the increased core thickness [12, 13]. Many software like Abaqus software were used to analysis composite sections [17]. It was found previously that increasing the thickness of lower angles in connection in composite sections caused an increase in energy dissipation of connections and a decrease in the induced initial stiffness from post-tensioned strands [17].

This article consists of: research significance, numerical modeling, experimental part, results, and conclusions. Results obtained from experimental tests were analyzed and compared with the predicted ultimate loads. Results also were obtained from ANSYS software and the theoretical extremes of both of states: fully-composite and non-composite. The investigation of changing properties of wythes is detailed in discussion section to determine the optimum concrete grade, concrete thickness, and core material. The following figure shows the flow chart of methodology of this research.

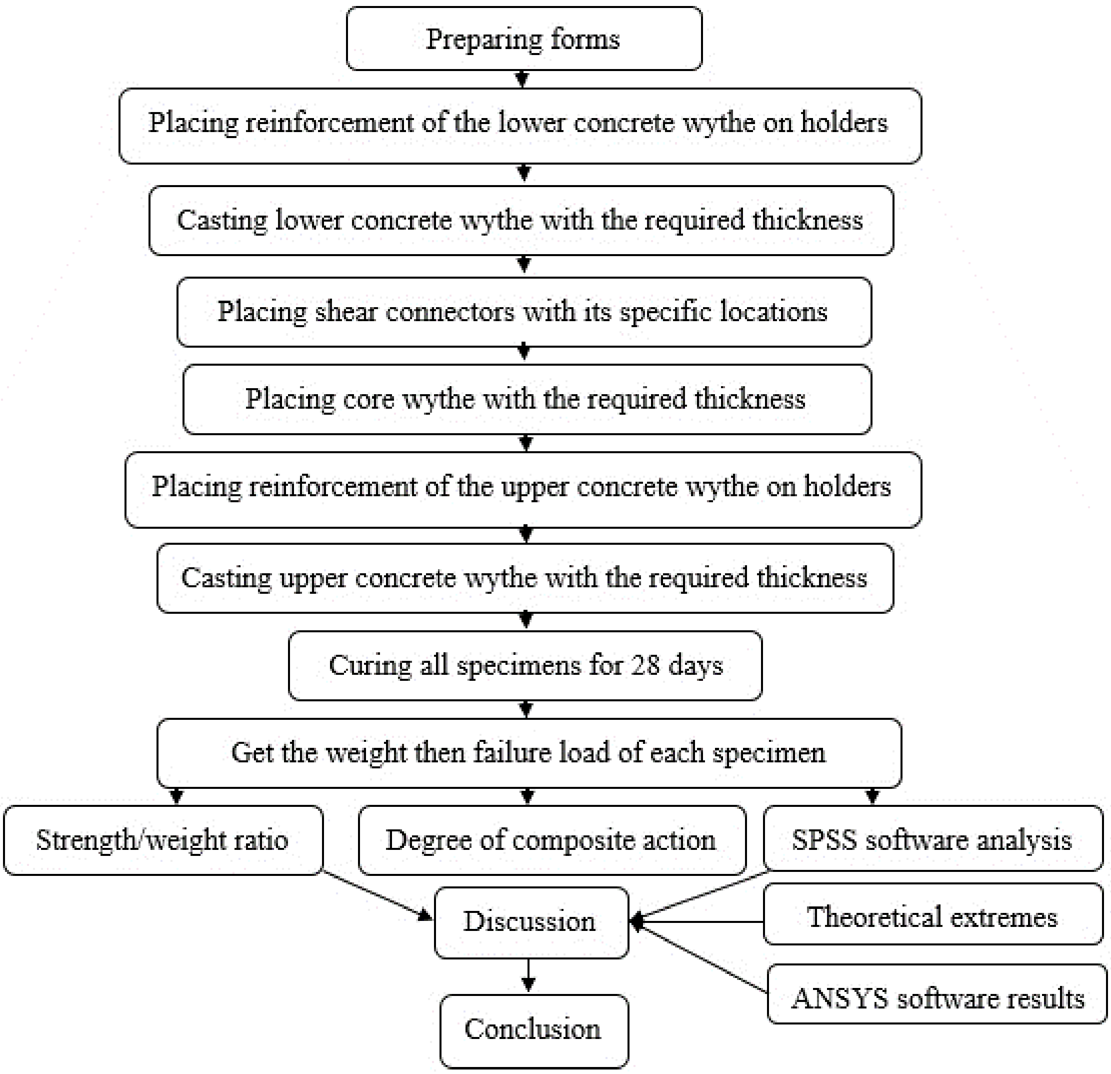

Figure 1. The flow chart of Study

Structural lightweight precast sandwich panels were used worldwide latest decade. It can provide the optimum solution between weight, heat insulation, and strength. Its efficiency depends on the degree of composite action achieved by structural behavior in case of loading, light weight, and the ability of heat insulation [14, 16]. Therefore, it was increasing demand worldwide to determine the optimum composite system of structural sandwich panels. Many parameters can be changed to enhance the structural behavior of panels. In this research, the input parameters were: the type of outer face concrete wythes, the thickness of them, and the type core insulation material. Those parameters were changed to achieve the optimum incorporation components that approach composite action [4]. Core wythe should be taken into consideration to perform the role of it: heat insulation and lightweight [13]. Strength\weight ratio should also have studied to get effective parameter that can judge the panels.

2. Numerical Simulation

The predictions of failure capacities were obtained from ANSYS 18.2 software. Mesh properties were adaptive size function with the element size of 95 mm and with the coarse relevance enter with minimum edge length of 18.85 mm as shown in Figure 2. Materials were defined in engineering data was concrete (with edited density and compressive strength of each concrete type) and steel (with fatigue data at zero mean stress comes from 1998 ASME BPV code, section 8, Div2 Table 5-11-1. Then the model was solved with the software to get the ultimate load. The ultimate loads obtained from the software were compared with the experimental ultimate loads. Figure 15 shows the equivalent stress in numerical modeling and Figure 16 Shows the equivalent elastic strain in numerical modeling. Failure shape and deformation of numerical modeling are shown in Figure 13. The predicted overall ultimate failure loads from the software are shown in Table 6.

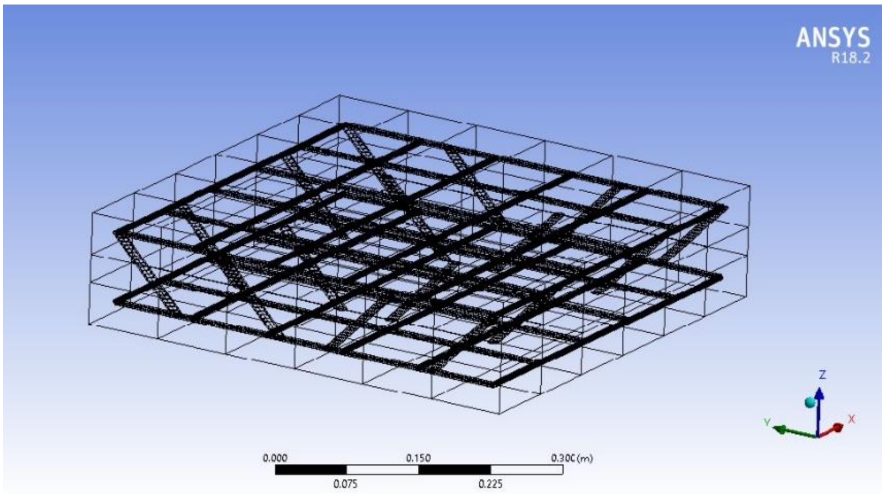

Figure 2. Mesh of specimen in ANSYS 18.2 software

3. Objectives and Items of Investigation

It was noticed that the efficiency of precast sandwich panels depends also on its weight and the ability of heat isolation and overall strength [2, 3]. Therefore, the main objectives of this study can be summarized as the following: obtaining a high (strength\weight) ratio by increasing strength of slabs with a lighter weight of slabs, approaching fully-composite action as possible by choosing the optimum type, the thickness of concrete, and core material. The ultimate load obtained from experimental tests was compared with the theoretical extreme capacities for each slab (100% degree of composite and 0% degree of composite) in the form % composite.

Fully composite state occurs when the specimen behaves a solid slab with total thickness of 120 mm. Non-composite state was obtained when each concrete wythe behaves alone. The main role of shear connectors is transferring shear between concrete wythes. Changing variables causes occurring of composite action with different degrees. Extreme capacities in both states are shown in Table 6. Calculations of capacities in both states [15] can be detailed as following equations from (1) to (11) [4, 15]. Comparisons between specimens were performed to determine the optimum components. Used parameters were concrete grade, concrete thicknesses and core material.

$$As = 169.56\, mm^2 \tag{1}$$

$$Fs = As \times fy = 47476.8\, kN \tag{2}$$

$$a = \frac{(As \times fy)}{(0.85 \times Fcu \times b)} \tag{3}$$

a) *Non-composite state: (for thicknesses of 25, 35 and 45 mm)*

$$x = \frac{a}{0.9} \tag{4}$$

$$d1 = \frac{(Thickness\ of\ one\ concrete\ wythe)}{2} - (\frac{x}{2}) \tag{5}$$

$$Mu = 2 \times ((As \times Fy) \times (d1 - (\frac{a}{2}))) \tag{6}$$

$$Pu = \frac{8 \times Mu}{L} \tag{7}$$

b) *Fully-composite state: (for thickness of 120 mm)*

$$x = \frac{a}{0.9} \tag{8}$$

$$d1 = \frac{(120\ mm)}{2} - \left(\frac{x}{2}\right) \tag{9}$$

$$Mu = ((As \times Fy) \times (d1 - (\frac{a}{2}))) \tag{10}$$

$$Pu = \frac{(8 \times Mu)}{L} \tag{11}$$

Where;

As = Area of tension reinforcement;

b = Per meter length of panel;

fy = Steel yield stress;

Fs = Force in tension reinforcement;

F_{cu} = Concrete characteristic strength;

a = Depth of neutral axis measured from the more highly compressed face;

Mu = Ultimate moment capacity under flexural;

Pu =The total load resisted by the panel;

$d1$ = Depth of the neutral axis.

4. Experimental Program

Seven specimens were prepared in the experimental program. The size of all specimens is 500×500 mm with total height of 120 mm. Three grades of concrete (80.3, 70.4, and 37) MPa, three thicknesses of upper and lower concrete wythes (25, 35, and 45 mm), and three types of core materials (high density foam, polyethylene foam and palm bark) were used in production of specimens. Each specimen consists of upper and lower wythes of reinforced concrete (5Φ 6mm per meter length) plain steel reinforcement in both directions in the middle of concrete wythes and core insulation material. In each specimen, 16 pieces of steel shear connectors with diameter of Φ12 mm were installed with angle of 45° in its specific positions. The total contents of specimens is shown in Table 1.

Table 1. Table of components of specimens

No.	Concrete		Core		Shear connector Type, Diameter (mm)
	Type	Thickness (mm)	Type	Thickness (mm)	
1	HSC	45	HD Foam	30	Steel Φ (12)
2	LHSC	45	HD Foam	30	Steel Φ (12)
3	LHSC	45	PE Foam	30	Steel Φ (12)
4	LHSC	45	Palm Bark	30	Steel Φ (12)
5	LWC	45	HD Foam	30	Steel Φ (12)
6	LHSC	25	HD Foam	70	Steel Φ (12)
7	LHSC	35	HD Foam	50	Steel Φ (12)

4.1. Materials

Ordinary Portland cement (OPC) CEMI 42.5N, silica fume, and quartz powder were used in the production of concrete wythes. Three types of core insulation were used: high density foam, polyethylene foam, and palm bark. The specific gravities of the materials are listed in Table 2. A polycarboxylic ether based superplasticizer complying with ASTM C494 (Type G) was used in the production of concrete. The chemical analysis of cement and silica fume and quartz powder are listed in Table 3. River sand, dolomite, and Leca coarse aggregates were used. The characteristics and the ingredients of three grades of concrete are listed in Table 4. Plain mild steel was used in the main reinforcement of concrete. Steel shear connectors with diameter of steel 12 mm were used. The specified tensile strength of steel is in Table 5.

Table 2. The specific gravity of the materials

Material	Specific gravity
Sand	2.66
Cement	3.15
Dolomite	2.60
Quartz powder	2.70
Silica fume	2.15
Leca aggregates	2.42
Superplasticizer	1.15

Table 3. Chemical analysis of cement, silica fume and quartz powder

	OPC	Silica fume	Quartz Powder
SiO_2, %	21.58	96.02	0.97
Al_2O_3, %	4.94	1.01	0.83
CaO, %	61.09	–	1.02
MgO, %	1.65	0.18	0.21
SO_3, %	3.22	0.26	0.33
Na_2O, %	0.5	0.14	0.05
K_2O, %	0.18	0.35	0.22
Fe_2O_3, %	3.56	0.52	0.35
Cl_2 %	–	0.16	0.05
Loss of ignition, %	2.60	–	–

Table 4. Characteristics and the ingredients of three grades of concrete.

Concrete type	HSC (High strength concrete)	LHSC (Light high strength concrete)	LWC (Light weight concrete)
Characteristic strength (MPa)	80.3	70.4	37
Density (kg\m³)	2660	2440	1800
Cement (kg\ m³)	450	950	555
Sand (% of cementitious)	115%	66%	60%
Dolomite (% of cementitious)	300%	0	0
Leca aggregates (% of cementitious)	0	0	65%
Quartz Powder (% of cementitious)	0	23%	0
Silica fume (% of cement)	0 %	30%	42%
Superplasticizer (% of cementitious)	2%	3.8%	2%
Water (% of cementitious)	19%	17.2%	39%

Table 5. Characteristics of steel shear connectors

Characteristic	Steel Bars
Dimensions in. (mm)	Bars with diameter (12)
Specified tensile strength (kN/mm^2)	0.8

4.2. Preparing Specimens

The sequence of preparing specimens is shown in Figure 3. Shear connectors were installed in its specific locations shown in Figure 4. Cross section for one specimen is shown in Figure 5.

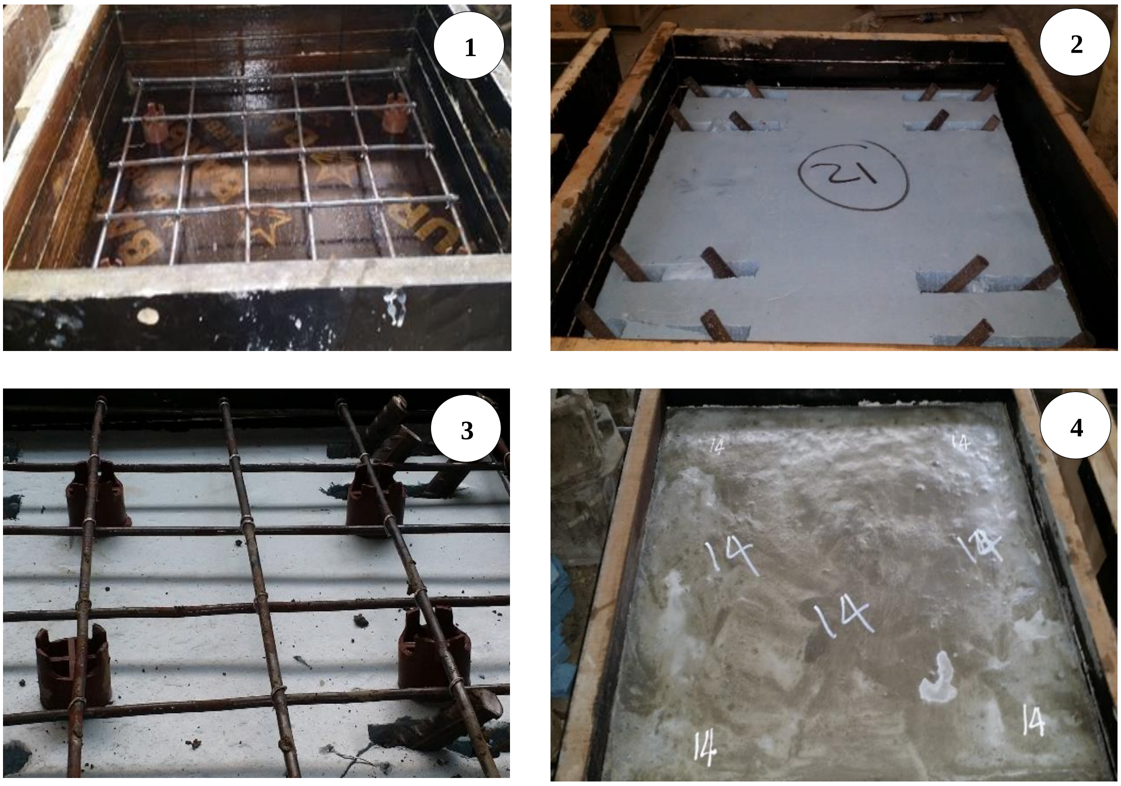

Figure 3. Sequence of preparing panels

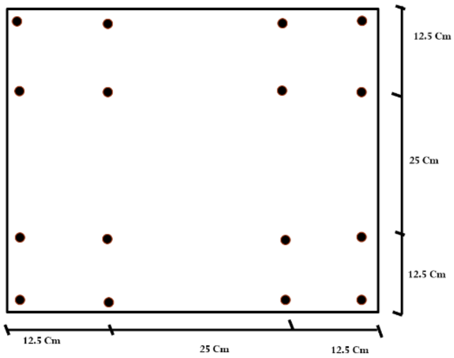

Figure 4. Distribution of shear connectors

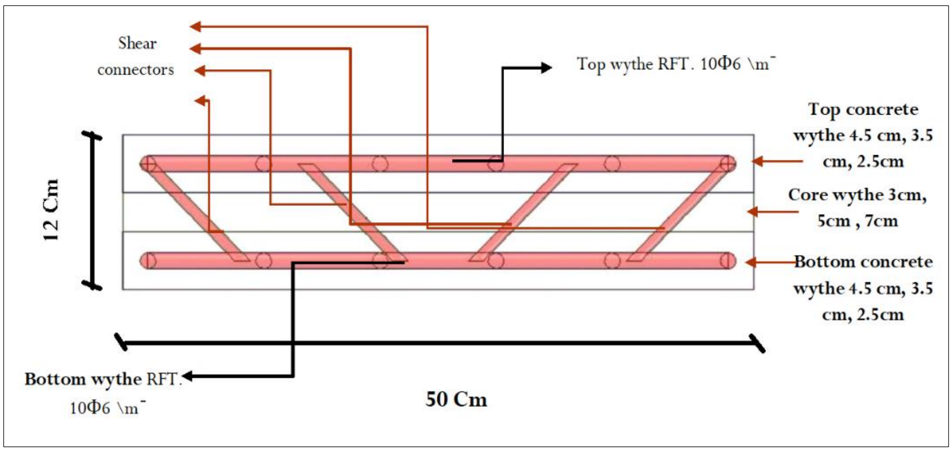

Figure 5. Cross section for one specimen

4.3. Items of Investigation

Seven specimens were tested under flexural load by three-point loading system as shown in Figure 6. The weight of each specimen was obtained with calibrated weight scale to get strength\weight for each specimen. Results and strength\weight are shown in Table 7. Characteristic strength and density for each grade are shown in Table 4.

Figure 6. Flexural test at laboratory

5. Results and Discussion

5.1. Results

The ultimate strengths which were obtained from the experimental flexural test are shown in Table 6. This ultimate strength was compared to the theoretical extreme in fully composite state (100% composite) to get the percentage of composite. The degree of composite of all specimens are included in Table7 and results of ANSYS 18.2 software are shown in Table 6. Table 7 also shows the degree of composite (%), weight, and (strength\weight) ratio. The comparisons of the predictions using the analytical model that developed in this study and theoretical and experimental results from the testing described above were performed to get the conclusion of the research and the optimum parameters of it.

The highest value of actual failure load and the degree of composite action were those of specimen 03 containing LHSC with the thickness of 4.5 cm and the polyethylene foam as core material. The highest strength/weight ratio was that of specimen 06 containing LHSC with the thickness of 2.5 cm by 1.40 kN/kg. Then, that of specimen 01 containing HSC with thickness of 4.5 cm and high-density foam by 1.17kN/kg. Also, it was noticed that specimens contain polyethylene foam were the nearest specimen which can be simulated numerically in ANSYS software and obtained the high ratio of predicted overall failure loads. In general, the upgrading grade of concrete increased significantly the total strength of slabs, the composite degree, and strength\weight ratio but the upgrading grade opposites increasing weight must be under control to observe the ratio (strength/weight). The lightweight concrete (37 MPa) and the high strength concrete (80.3 MPa) were effective in panels than light high strength concrete (70.4 MPa). That was because of very lightweight of LWC and very high strength of HSC that increased the overall (strength/weight) ratio. Generally, it was found that decreasing thickness of concrete face wythes had a positive effect on strength/weight ratio (although the ultimate loads decreased) that enhanced the performance of panels as light weight structural panels.

Failure shapes at experimental and ANSYS software are shown in Figure 13 and Figure 14. The experimental failure shape and deformation is similar to the failure shape of the numerical model especially in the 15 cm in mid-span. That proved that the numerical modeling presents specimens perfectly.

The range of results of degree of composite action degree (in form of %) of this study was almost the same range of some similar previous studies that exist in the references. The Table 8 shows the range of values of composite action in different studies.

Table 6. Results of experiments, ANSYS and theoretical extremes.

No.	ANSYS Failure Load (kN)	Actual Failure Load (kN)	Theoretical non-Composite Load (kN)	Theoretical fully Composite Load (kN)
1	85.32	76.63	31.95	90.04
2	81.06	61.78	31.64	89.88
3	79.78	79.80	31.64	89.88
4	65.70	50.20	31.64	89.88
5	72.10	52.01	28.35	88.24
6	47.43	51.82	16.45	89.88
7	56.68	50.46	24.04	89.88

Table 7. The degree of composite (%), weight (Kg) and (strength\weight) ratio (kN\Kg)

No.	Degree of composite (%)	Weight (Kg)	(Strength /Weight) (kN/Kg)
1	85.11%	65.30	1.17
2	68.74%	60.35	1.02
3	88.79%	60.31	1.32
4	55.85%	60.28	0.83
5	58.94%	47.75	1.09
6	57.65%	36.95	1.40
7	56.14%	48.65	1.04

Table 8. The range of composite action degree comparing to previous studies

Parameter	Range (%)	Reference
Degree of composite action (%)	78-86	[3]
Degree of composite action (%)	24-91	[5]
Degree of composite action (%)	50-80	[6]
Degree of composite action (%)	94-100	[10]
Degree of composite action (%)	74-84	[12]
Degree of composite action (%)	73-89	[15]
Degree of composite action (%)	56-89	This study

5.2. Discussion

Concrete Grade's Effect:

Concrete grade was changed with different grades of concrete and cores materials to measure how it affects the ultimate strength and the degree of composite. Strength\weight ratio was calculated to measure the relative relationship between strength and weight. While comparing specimens 01 and 02, it was noticed that the ultimate strength decreased with change of HSC to LHSC by 19.3%, the degree of composite action decreased by 19.23%, and strength\weight ratio decreased by 12.8%. Furthermore, the strengths of the HSC panel and the LHSC panel were about 89.81% and 76.21% of the strengths obtained from ANSYS software respectively as shown in Figure 7 and Figure 8. When comparing specimens 01 and 05, the ultimate strength decreased with the change of HSC to LWC by 32.12%, the degree of composite action decreased by 30.74%, and strength\weight ratio decreased by 6.8%. Furthermore, the strength of the LWC panel was about 72.13% of the strength obtained from ANSYS software. When comparing specimens 2 and 5, the ultimate strength decreased by 15.8% when concrete changed from LHSC to LWC, also degree of composite action decreased by 14.2%, and by the way strength\weight ratio increased by 6.4% as shown in Figure 7 and Figure 8. The previous discussion revealed that the demand of light weight should be taken into consideration beside strength. Therefore, the smarter panels in overall (strength/weight) ratio is that of very high strength (80 MPa) or that of the very light-weight (37 MPa). In addition, that of the medium weight and strength (70 MPa) that didn't meet the optimum parameters comparing to the other panels. That because the opposite increase in (strength/weight) ratio was not significantly observed in LHSC.

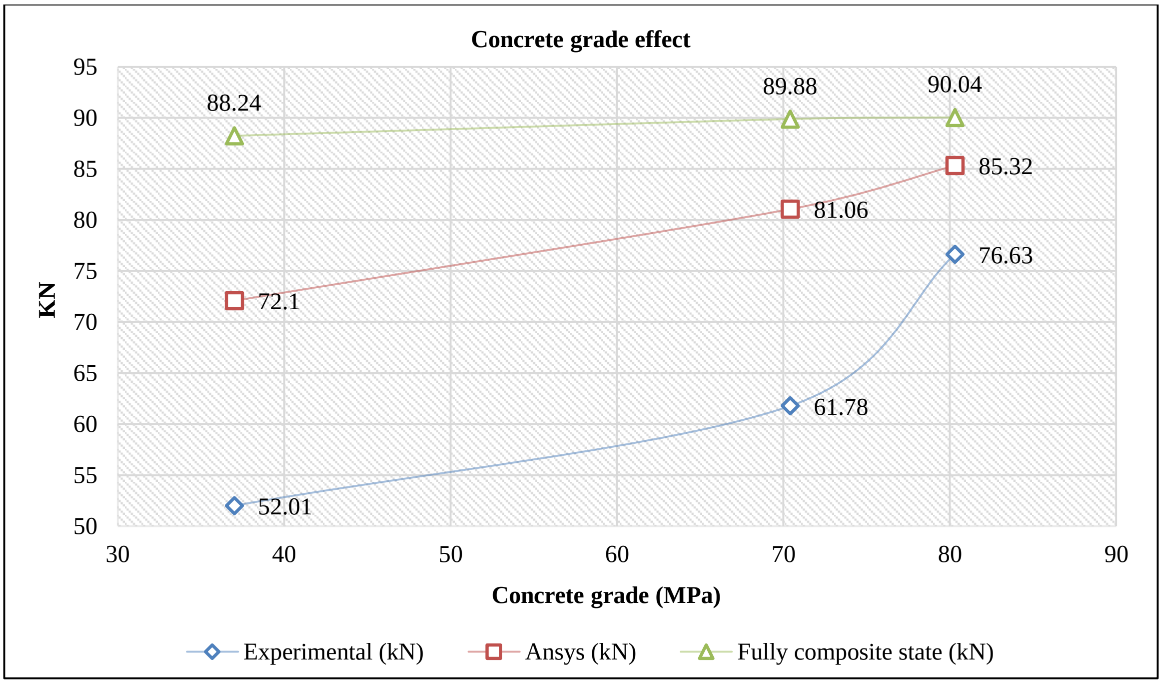

Figure 7. Concrete grade effect on experimental, theoretical and ANSYS capacities

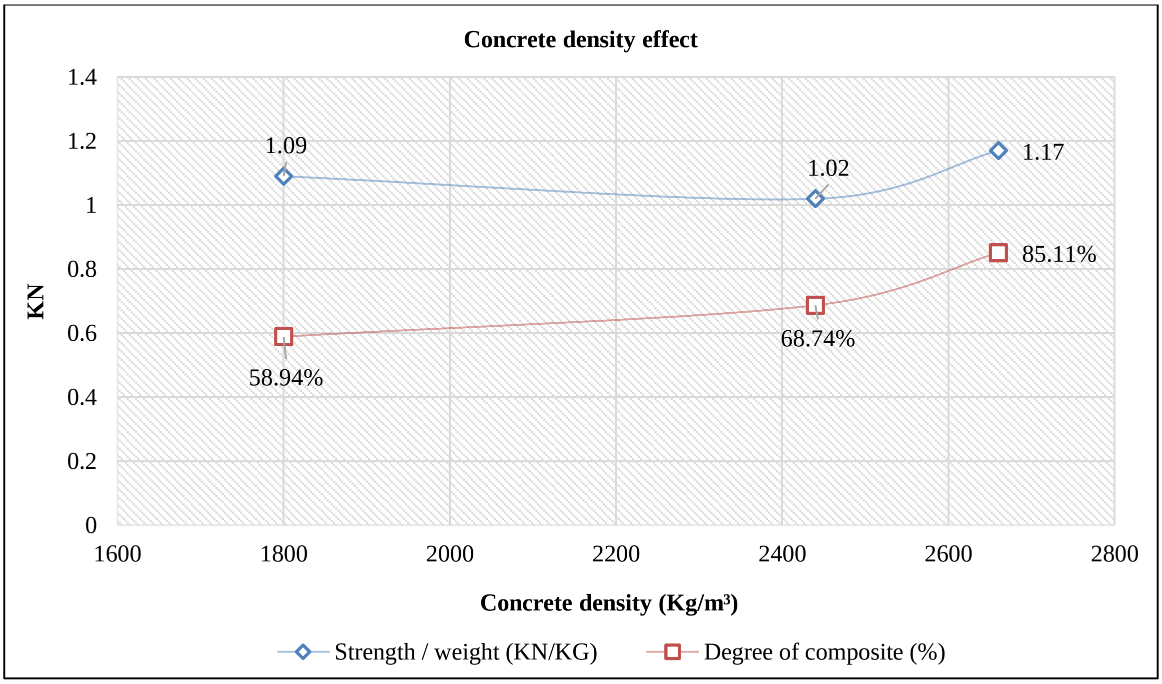

Figure 8. Concrete density effect on degree of composite and strength/weight ratio

Concrete Face Wythe Thickness's Effect

Concrete face wythe thicknesses have been changed between different three values. That parameter can judge the panels well because the decreases of the wythe thickness. When it decreases, the ultimate capacity decreases and the overall weight of the panel decreases leading to increasing (strength/weight) ratio. Changes in load capacity, composite degree, and strength\weight were observed. When comparing specimens 2 and 7, the ultimate load and the degree of composite decreased by 18.32%, but the (strength/weight) ratio increased slightly by 2% when the thickness of both wythes changed from 45 mm to 35 mm. The ANSYS results revealed that the experimental results achieved 76.21% and 89. % from software results respectively for the panel with thicknesses of 45mm and 35mm. When comparing specimens 6 and 7, the ultimate load increased by 3%, the degree of composite increased by 3%, and strength\weight increased by 25% when the thickness changed from 35mm to 25mm as shown in Figure 9. The observed change in strength\weight ratio is subjected to the increased weight of slab due to increasing of concrete wythe. That increase was with slight change in ultimate load. When comparing specimens 2 and 6, it was observed that the ultimate load decreased by 15.8% when the wythe thickness decreased from 45mm to 25mm, also composite action decreased by 16.1% on the other side the strength\weight ratio increased by 13.3% as shown in Figure 10. The enhanced flexural behavior was observed with the thickness of 4.5 cm and it decreases with decrease of thickness. On the other hand, the smarter panel is that of face thicknesses of 2.5 cm which achieved the highest (strength/ weight) ratio of 1.4 kN/kg.

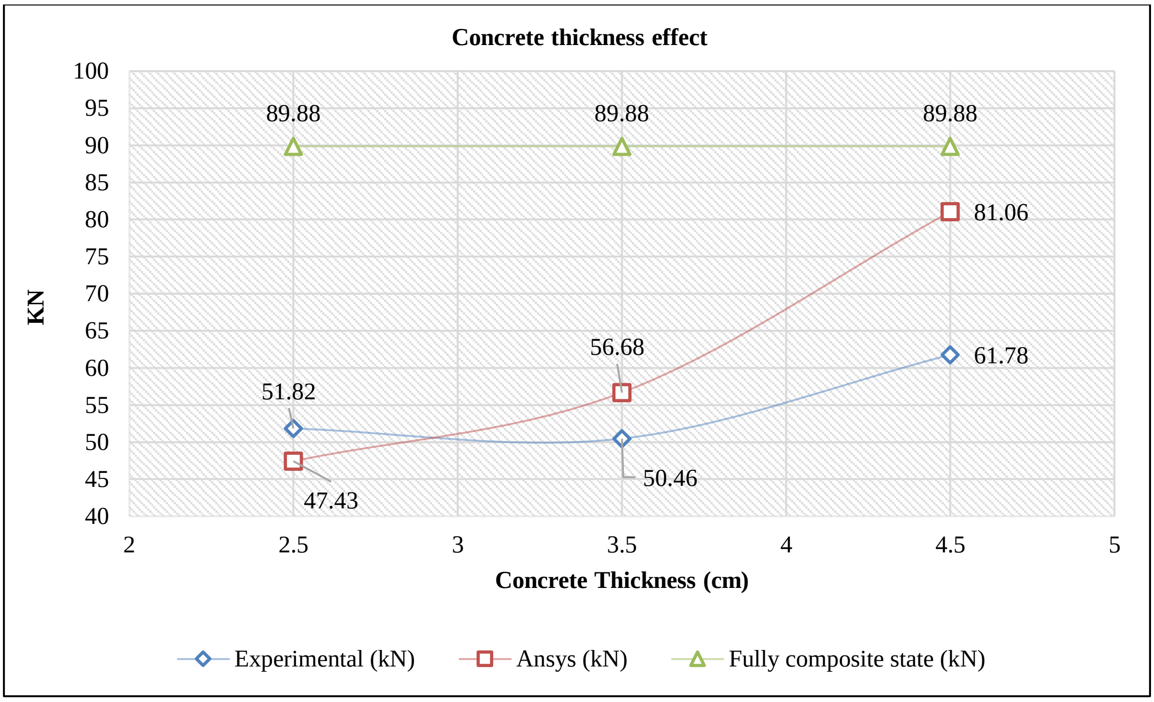

Figure 9. Concrete thickness effect on experimental, theoretical and ANSYS capacities

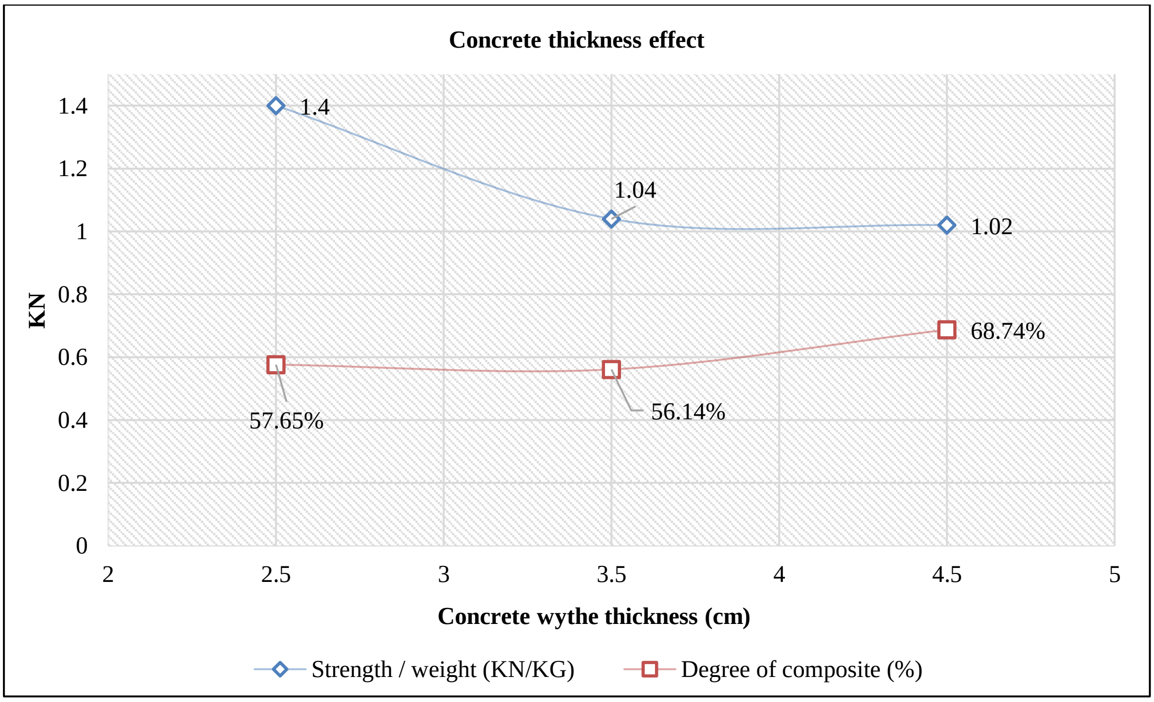

Figure 10. Concrete thickness effect on degree of composite and strength/weight ratio

Core Material Effect:

Core material should be quite rigid to resist the shear transfer between two concrete wythes. It also has enough flexibility to transfer few forces during the test. That can be affected indirectly approaching the composite action.

When comparing specimens 2 and 3, the ultimate load and the composite degree increased by 22.5%, and strength\weight increased by 22.7% when core material was changed from HD foam to PE foam.

The panel contains PE foam achieved approximately the ANSYS result that presents 89% of theoretically fully composite state. When comparing specimens 2 and 4, the ultimate load and the composite degree decreased by 19%, and strength\weight decreased by 19% when core material was changed from HD foam to palm bark as shown in Figure 11. When comparing specimens 3 and 4, it was found that the ultimate load and composite action decreased by 37% when core material changed from PE foam to palm bark and strength\weight ratio decreased by 37.1% as shown in Figure 12. That parameter revealed that the PE foam is the best core material which provides light weight, enough flexibility, and enough rigidity to transfer slight internal forces. It was observed that PE foam has the ability to present core material in composite section in ANSYS software.

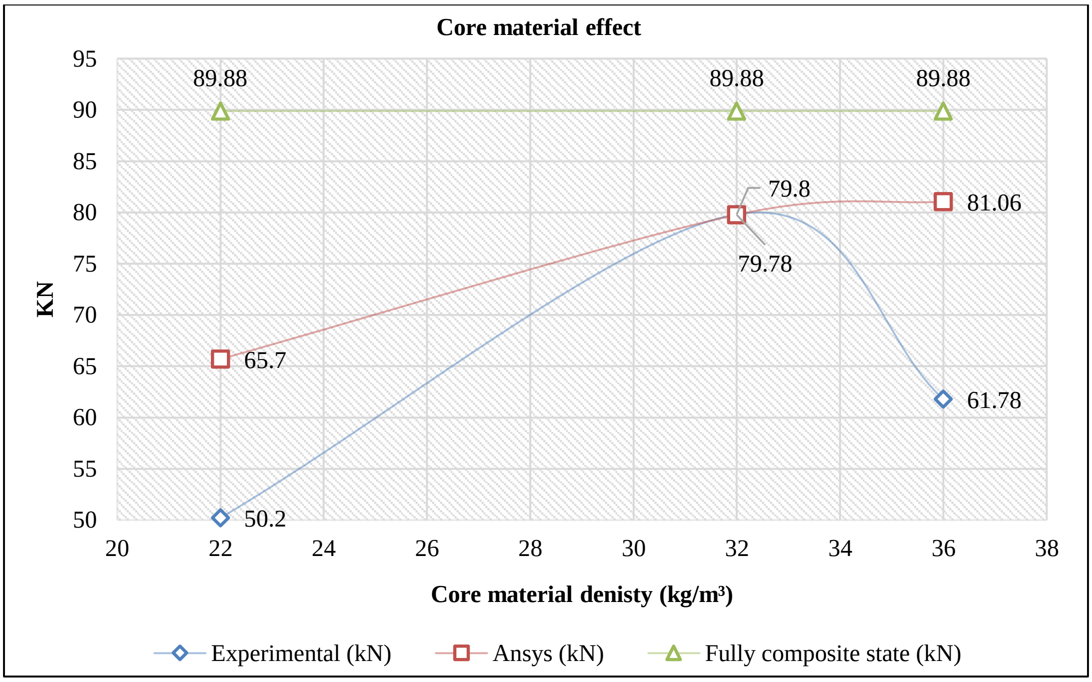

Figure 11. Core material effect on experimental, theoretical and ANSYS capacities

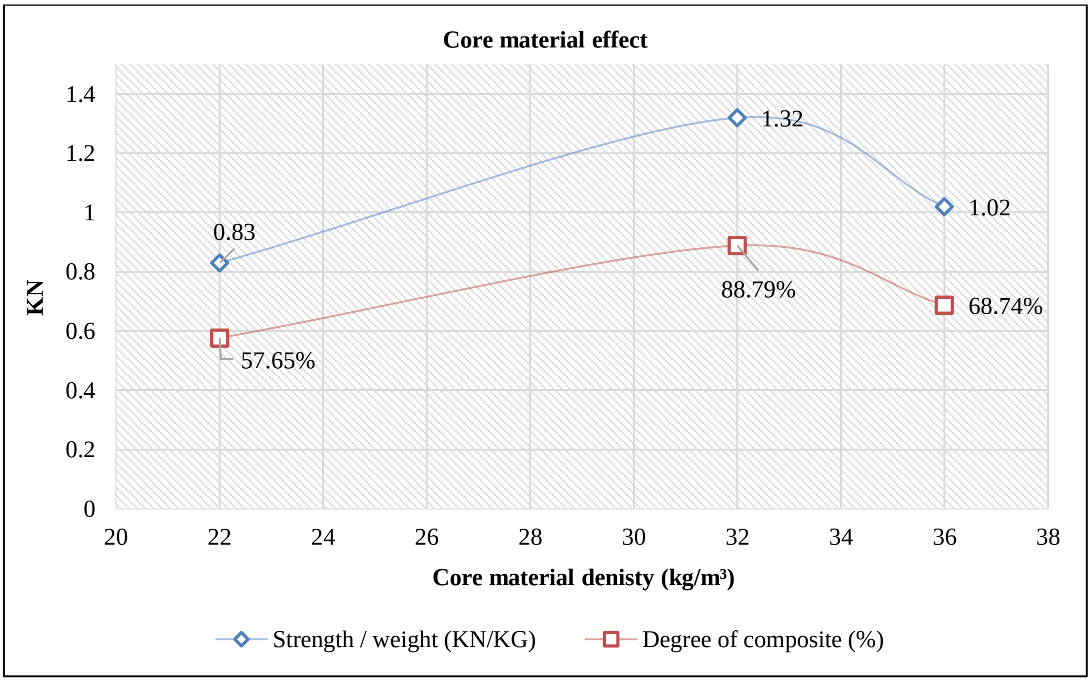

Figure 12. Core material effect on degree of composite and strength/weight ratio

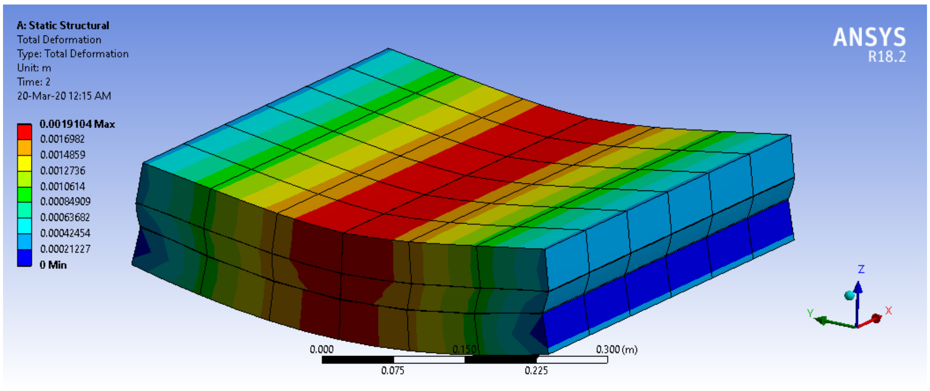

Figure 13. Failure shape in ANSYS 18.2 software

Figure 14. Failure shape at experiment

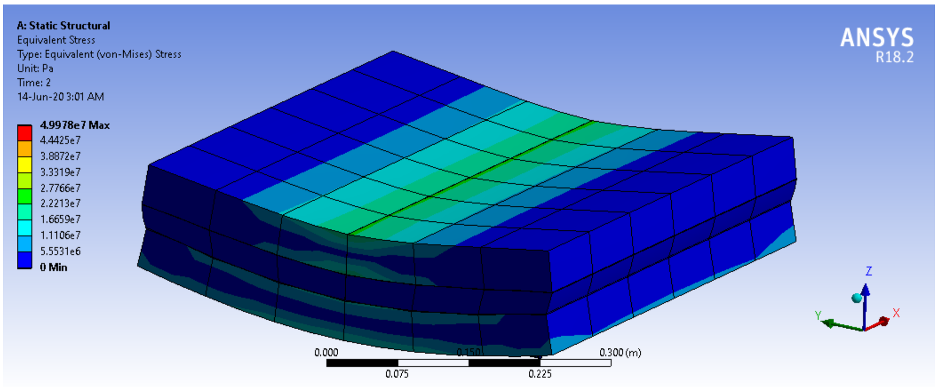

Figure 15. Equivalent stress in numerical modeling

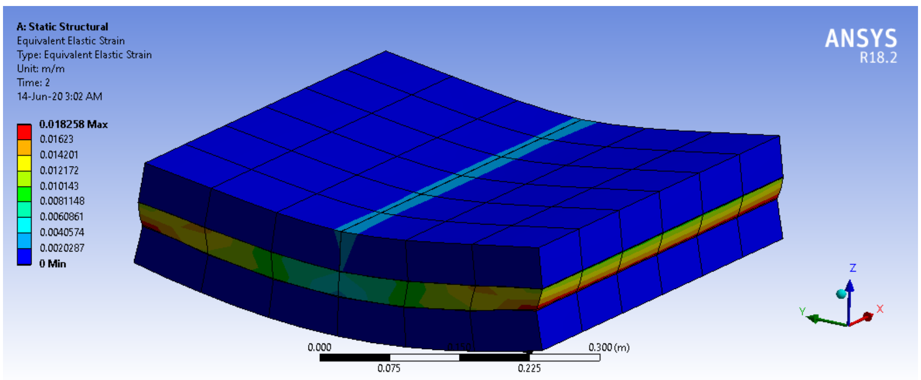

Figure 16. Equivalent elastic strain in numerical modeling

Analysis with SPSS Software:

Experimental results were analyzed with the aid of SPSS software program to get correlation and determine significantly for each parameter (concrete grade, concrete thickness, and core material). Analysis type was multi dunken's multiple range test (0.05) with separated parameters. Results were shown in Table 9.

Table 9. SPSS software results

Parameter	NO. of specimens	Correlation	Level
Concrete Grade	1 , 2 , 5	Significant	0.05 (2-tailed)
Concrete Thickness	2 , 6 , 7	Significant	0.01 (2-tailed)
Core Material	2 , 3 , 4	Significant	0.01 (2-tailed)

6. Conclusions

Based on the results of this experimental investigation under tidal environment, the following conclusions are drawn as following:

- High strength concert (HSC) and light weight concrete (LWC) are very successful in the production face wythes of precast light weight sandwich panels.
- Although the loading capacity of panels increased with the increase of face wythes thicknesses, the overall weight of panels increases.
- The optimum face wythe thickness is the that of 2.5 cm which has high (strength/weight) ratio of 1.4 kN/kg although it has relatively low ultimate capacity.
- Adding polyethylene foam as a core material results positive effect on structural sandwich panel. It results high (strength/weight) ratio of 1.32 kN/kg because of its relative lightweight and flexibility.
- The polyethylene foam was the nearest core material which presented its real role in modeling of ANSYS software because of it enough rigid and flexible to transfer internal forces in panel.
- In general, upgrading grade of concrete increased significantly the total strength of slabs, the composite degree, and strength\weight ratio. On the other hand, when upgrading grade opposites increasing weight must be under control to observe the ratio (strength/weight). The lightweight concrete (37 MPa) and the high strength concert (80.3 MPa) were effective in panels than light high strength concrete (70.4 MPa). That was because of very lightweight of LWC and very high strength of HSC which increased the overall (strength/weight) ratio.
- Generally, it was found that the optimum thickness is 2.5 cm, the optimum core material is polyethylene foam, and the optimum type of concrete is high strength concrete (80 MPa and density = 2660 kg/m^3).
- Analysis with SPSS software program showed that all parameter correlations (concrete grade, concrete thicknesses and core materials) were significant.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. Nomenclature

SPSP = Structural precast sandwich panel;

HSC = High strength concrete;

LHSC = Light high strength concrete;

LWC = Light weight concrete;

HD foam = High density foam;

PE foam = Polyethylene foam;

Palm bark = the bark of palm tree;

Steel Φ 12 mm = Steel reinforcement with diameter of 12 mm.

9. References

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