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An overview on syntactic foam core and paper skin sandwich composites as potential building materials

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ABSTRACT
Novel sandwich composites made of syntactic foam core and paper skin were overviewed as potential building materials. Interface bonding between core and skin were controlled by varying starch content. Two different microsphere size groups were employed for syntactic foam core manufacturing based on the pre-mould processing method. Properties of skin paper with starch adhesive on were found to be affected by drying time of starch. Mechanical behaviour of manufactured composites in relation with properties of constituents was studied. Skin contributed to increase up to 40% in estimated flexural strength over syntactic foams, depending on starch content in adhesive between core and skin. Smaller microsphere size group for core was found to be advantageous in strengthening sandwich composites for a given starch content in adhesive. Failure process of sandwich composites was discussed in relation with load-deflection curves. Core cracking was detected to be the first event in sandwich composite failure sequence.

Keywords: Sandwich composite, Syntactic foam, Paper, Starch, Manufacturing, Properties.

1. Introduction
Sandwich composites have been adopted in various areas ranging from building to aircraft/space industries. They are made to be light and stiff for structural components subjected to particularly flexural loads. Various types of sandwich composites can be made by selecting different constituent materials for core and skins. For the selection of constituent materials, factors such as properties and cost may be considered. In building industry, material cost is a driving force in selecting materials since large quantities of materials are required. In applications for interior walls and ceilings, material weight is an important consideration for installation and performance. There have been efforts to reduce the material density in such applications by forming gas bubbles in gypsum as core of sandwich [1].

Recently, Islam and Kim [2] have developed novel syntactic foam, which may be suitable as core material for low density sandwich panel. The developed syntactic foam itself is a composite made of hollow microspheres and starch. The hollow microspheres are available as part of fly ash from coal-fire power stations. In India, for example, the production of fly ash as pollutant is expected to be over 140 million tons in 2020 and waiting to be utilized [3]. The starch has some advantages over other binders such as epoxies, phenolics, etc in applications for building interior sandwich panels because it is readily available, environmentally friendly, inexpensive, and renewable. The developed syntactic foam can further be useful with paper skin for development of sandwich composites, given that paper as skin is an inexpensive option. When aforementioned constituent materials are used for manufacturing sandwich composites, the mechanical performance of sandwich composites is generally affected by (a) bonding condition between core and skins requiring consideration of parameters such as microsphere size, (b) starch permeation into paper and (c) starch concentration which are not normally considered in other types of sandwich composites [4-7]. Such parameters would be potentially important in continuous mass production for optimization when starch is used.

In the present work, novel sandwich composites made of constituent materials described above were developed and their mechanical behaviour was studied in relation to constituent properties and fabrication conditions.

2. Constituent materials
Ceramic hollow microspheres (composed of silica 55-60%, alumina 36-40%, iron oxide 0.4-0.5% and titanium dioxide 1.4-1.6%) supplied by Envirospheres Pty Ltd, Australia were used for syntactic foam manufacture. Two different size groups (or commercial grades), SL75 and SL300, with size ranges 31-83 and 101-332 μm respectively for 95%, were employed. The particle densities of SL75 and SL300 were measured to be 0.68 and 0.80 g/cc, and the bulk densities to be 0.39 and 0.43 g/cc respectively.

Potato starch (Tung Chun Soy & Canning Company, Hong Kong) was used after gelatinization as both binder and adhesive for microspheres of syntactic foams and attachment of skin paper to syntactic foam core respectively for sandwich composites. Particle density and bulk density of the potato starch were found to be 1.50 and 0.85 g/cc respectively.

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Syntactic foam cores were prepared with two different microsphere size groups (SL75 and SL300). Details of manufacturing are given below. Three different types of adhesive between skin and foam core were prepared by varying starch concentration in water i.e. three mass ratios of water to starch, 14/1, 30/1 and 70/1. Brown plain paper (Visy Paper, 180 g/m^2 in mass and 0.30 mm in thickness) was used as skin for sandwich composites.

3. Syntactic foam panel manufacture

Syntactic foam panels based on the pre-mould method [8] were manufactured. Starch binder was first prepared. A mixture of starch particles and water in a container was heated until the gelatinisation fully occurred. The mixture (now binder) was cooled down to room temperature. Hollow microspheres were added to the prepared binder in a container. Stirring of the resulting mixture was then conducted after sealing the container. The mixture container was left for 30 minutes to allow for phase separation caused by buoyancy of microspheres and gravity of starch. The top phase consisted of microspheres and binder, bottom phase consisted of starch rich binder as sediment and middle consisted of water. The bottom two phases were drained out through a hole at the bottom of the container and the left mixture was directly transferred using a scoop into an open mould. The molded mixture was placed in an oven at 80°C for 7 hours.

Four different types of syntactic foam were manufactured. They were coded as SLxxWSxx. For example, SL75WS50 is for microsphere size group, SL75, and a mass ratio of water to starch, 50/1. Thus, the manufactured syntactic foams are SL75WS50, SL300WS30, SL75WS70, and SL300WS50.

4. Skin paper for tensile properties

Three different specimen types for tensile properties of skin paper were prepared. First type was for specimens without starch adhesive, second and third types were coated with starch adhesive in two different ways of drying starch adhesive. For both second and third types of skin paper, starch adhesive prepared with a ratio of 30/1 for water to starch was applied to skin paper using a roller with a single stroke of motion to control starch content. Subsequently, for the second type (slowly dried), skin paper was enveloped in wet cloth carefully not to be in contact with each other in a small chamber but to slow down drying starch adhesive for four hours at room temperature and then finally fully dried in an oven. For the third type (fast dried), skin paper was just left in laboratory ambience for four hours at 20°C and then placed in an oven at 50°C until fully dried.

5. Sandwich composite fabrication

The paper skin was cut into rectangles with dimensions of 86 x 26 mm. Starch adhesive was applied to the paper skin using a roller with a single stroke of motion to control starch content on the paper skin. Sandwich composites were fabricated by attaching skin paper with starch adhesive on to top and bottom surfaces of syntactic foam core. To maximize contact area between paper skin and syntactic foam core, four layers of sandwich composite between two aluminum plates were stacked up with soft inserts between sandwich composites so that the sequence of the lay-up is made of aluminum plate, Cling wrap, two layers of paper towel, Cling wrap, sandwich composite, so on. The lay-up was left at room temperature for 4 hours and then placed in an oven at 50°C up to 8 hours until no mass change was observed.

Sandwich composites manufactured will be referred to as SLxxWSxx-WSxx for microsphere size group used and mass ratio of water to starch for syntactic foam binder as previously denoted for syntactic foam panels, and, in addition, mass ratio of water to starch for starch adhesive between skin paper and syntactic foam core. For example, SL75WS50-WS30 denotes that microsphere size group is SL75 with a mass ratio 50/1of water to starch for syntactic foam binder, and mass ratio of water to starch for adhesive between skin paper and core is 30/1.

6. Mechanical testing and calculations

All mechanical tests were conducted on a universal testing machine (Shimadzu 5000) at a crosshead speed of 1.0 mm/min and at an ambient temperature range of 18-21°C. Three point flexural tests with a span length (L) of 63.5 mm were conducted for syntactic foam panels and sandwich composites (Fig.1).

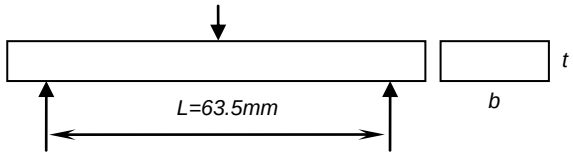


Fig.1 Three-point loading for flexural tests.

Flexural modulus (E) and stress (σ_f) for syntactic foam panels were calculated using the following equations given in ASTM D 790M – 93:

$$E = \frac{L^3 m}{4bt^3} \quad (1)$$

$$\sigma_f = \frac{3P_f L}{2bt^2} \quad (2)$$

where L is the support span, m is the slope of the tangent to the initial straight-line portion of the load-deflection curve, b is the width of panel, t is the thickness of panel, and P_f is the load. Flexural strengths (σ_{fc}) were calculated with the first peak load (P_{fc}). The maximum flexural strain (ε_f) for syntactic foam panels was also calculated using [9]:

$$\varepsilon_f = \frac{6t\delta}{L^2} \quad (3)$$

where δ is the mid span deflection. Tensile elastic modulus (E_t) for syntactic foam panels was calculated using [9]:

$$E_t = E_C \left(\frac{\sqrt{\frac{E}{E_C}}}{2 - \sqrt{\frac{E}{E_C}}} \right)^2 \quad (4)$$

where E_c is the compressive elastic modulus. Effective stiffness (S_{eff}) for sandwich composites was calculated using:

$$S_{eff} = \frac{EI}{b} \quad (5)$$

where I is given by $I = \frac{bt^3}{12}$, and t is the total thickness for skin and core in the case of sandwich composite. The location of neutral axis (y_0) [9] from the top surface (compression side) was calculated using:

$$y_0 = \frac{t}{1 + \sqrt{E_C / E_T}} \quad (6)$$

where E_T and E_C are tensile modulus and compressive modulus respectively. Average shear stress (τ_{av}) [10] produced by flexural loading was calculated using:

$$\tau_{av} = \frac{VQ}{Ib} \quad (7)$$

where V is the shear force, Q is the first moment about the neutral axis of the portion of the rectangular cross section which is located either above or below the location for which shear stress is to be calculated, and I is the moment of inertia of the entire cross sectional area about the neutral axis.

Tensile tests on paper skin for sandwich composites were conducted at a relative humidity of 51%. Specimen geometry and dimensions are given in Fig.2. All other test specimens were oven dried before mechanical testing unless otherwise stated.

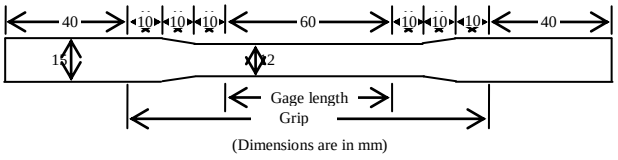


Fig.2 Tensile test specimen for skin paper.

7. Results and discussion

7.1 Constituent materials

Properties of syntactic foam panels for SL75WS50 and SL300WS30 are listed in Table 1. Two different microsphere size groups but a constant volume fraction of starch in foam was chosen. Flexural properties of both foam panels appears to be similar as expected from the common volume fraction of starch as previously discussed for compressive behaviour [2]. An example for flexural (maximum) stress versus maximum strain curve (grey line) obtained using Eq. (2) and (3) is given in Fig.3. It appears to be linear and no energy absorption after the peak load is seen. Images of fracture surfaces for SL75WS50 and SL300WS30 are given in Fig.4. Not much difference between compression and tension sides is found although it would have been possible to have more crushed microspheres on compression side than tensile side if inter-microsphere bonding was stronger.

Table 1 Properties of syntactic foam panels (starch volume fraction in both foams is 0.04). The 95% confidence intervals are given in parenthesis.

Syntactic foam	Flexural strength, σ_{fc} (MPa)	Flexural modulus, E (GPa)	Compressive modulus†, E_c (MPa)	Tensile modulus††, E_t (GPa)	Density (g/cc)
SL75WS50	7.89 (±1.50)	1.06 (±0.07)	167 (±64)	4.00 (±0.93)	0.37
SL300WS30	7.57 (±0.80)	1.13 (±0.13)	146 (±67)	1.88 (±0.51)	0.44

† From reference [2]. †† Calculated using Eq. (4).

Table 2 Tensile properties of skin for three different types of preparation. Starch adhesive for coating was prepared with a ratio of 30/1 for water to starch. The 95% confidence intervals are given in parenthesis.

Tensile Strength (MPa)			Tensile Modulus (GPa)		
Without starch adhesive	Coated with starch adhesive (Fast dried)	Coated with starch adhesive (Slowly dried)	Without starch adhesive	Coated with starch adhesive (Fast dried)	Coated with starch adhesive (Slowly dried)
36.15 (±2.56)	36.37 (±1.34)	38.01 (±1.11)	0.96 (±0.03)	1.04 (±0.08)	1.10 (±0.05)

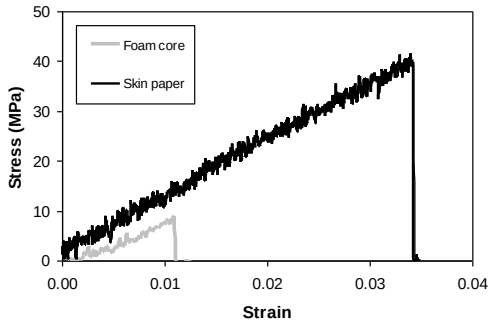


Fig.3 Examples for flexural (maximum) stress versus maximum strain curve (in grey) obtained using Eq. (2) and (3) for syntactic foam panel SL75WS50; and for tensile stress strain curve (in black) obtained from skin paper without starch adhesive on.

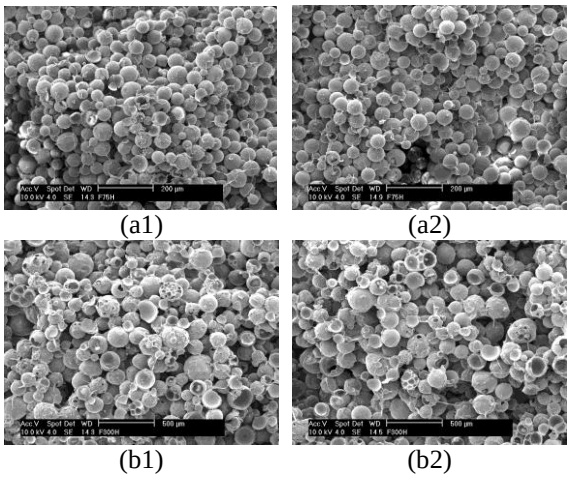


Fig.4 Scanning electron microscopic (SEM) images of fracture surfaces of syntactic foam panels from three-point flexural tests: (a1) compression side of SL75-WS50; (a2) tension side of SL75WS50; (b1) compression side of SL300WS30; and (b2) tension side of SL300WS30.

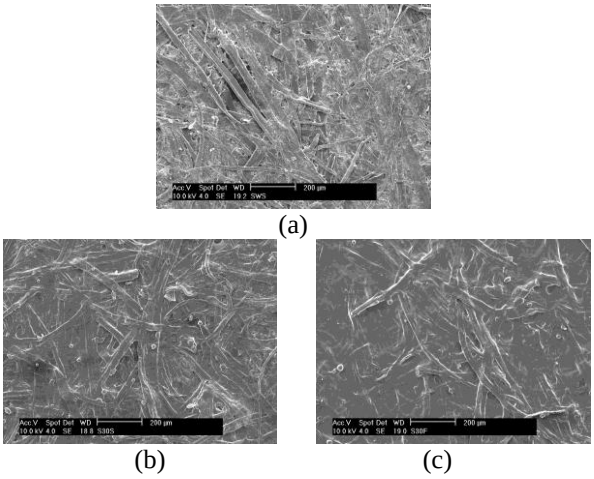


Fig.5 SEM images of typical skin paper surfaces: (a) without starch adhesive; (b) coated with starch adhesive, slowly dried; and (c) coated with starch adhesive, fast dried.

Tensile properties of skin paper for three different types of preparation were characterized and listed in Table 2. Results for the second (fast dried) and third (slowly dried) types were obtained from follow-up tests after realizing in the course of evaluation of sandwich composites that there might have been unknown effects of adhesive (between paper skin and core) on skin paper caused by adhesive drying process. Tensile strength and modulus of paper skin appear to increase by 0.6% and 8.3% respectively as a result of fast drying adhesive on, and further increase as a result of slow drying by 5.1% and 14.7% respectively. This indicates that the effect of starch adhesive is greater in stiffening than in strengthening. Fig.5 shows typical SEM images of skin paper surfaces prepared in three different ways. The number of fibre edge lines decreases and hence the level of details in the order of the first, second, and third types of preparation. The second type can further be compared with the third type for drying speed effect, indicating that gelatinised starch has permeated through the skin paper, giving more stiffening effect.

An example for tensile stress strain curve (black line) of skin paper is given in Fig.3. It appears to be linear and no energy absorption after the peak load is seen. Not much difference in behaviour between syntactic foam panel and skin paper is noticed even though a large difference in strength is found.

7.2 Sandwich composites

In general, mechanical performance of sandwich composites depends on adhesion strength between skin and core in addition to mechanical properties of constituent properties. When starch adhesive is used for skin and core for continuous production of sandwich, it is important to optimize starch content. It was previously discussed for pre-mould process that, there is a range of low viscosities in starch binder prior to a transition towards a higher rate of viscosity change [8]. (The transition takes place when a volume fraction of gelatinized starch sedimentation after two phase separation closely approaches one.) The low range of viscosities may be preferred for coating starch adhesive on skin paper for sandwich composite manufacture. Starch adhesives with three different starch mass ratios (water/starch), 14/1, 30/1, and 70/1 respectively were prepared for attaching skin paper to surfaces of syntactic foam core for sandwich composites. The ratio of 14/1 is higher and the other two ratios (30/1 & 70/1) are lower than the aforementioned transitional point. Measured starch contents on skin paper are listed in Table 3.

Table 3 Starch mass on skin paper after single stroke coating by a roller. The starch mass was measured after drying. The 95% confidence intervals are given in parenthesis.

Mass ratio of water to starch	Starch (mg/cm^2)
14/1	1.56 (±0.010)
30/1	0.51 (±0.006)
70/1	0.18 (±0.002)

Table 4 Three-point flexural test results for sandwich composites. The 95% confidence intervals are given in parenthesis.

Sandwich composite	First peak load per unit width (N/mm)	Effective stiffness, EI/b (Nm)
SL75WS50-WS14	12.67 (±0.683)	141 (±1.982)
SL75WS50-WS30	10.73 (±0.808)	128 (±7.585)
SL75WS50-WS70	9.31 (±0.430)	127 (±4.115)
SL300WS30-WS14	11.48 (±0.495)	104 (±1.608)
SL300WS30-WS30	10.58 (±0.740)	101 (±2.287)
SL300WS30-WS70	8.02 (±0.319)	101 (±2.007)

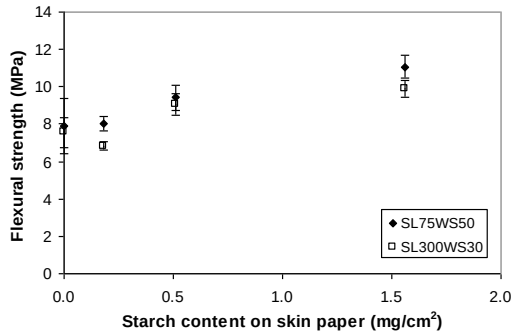
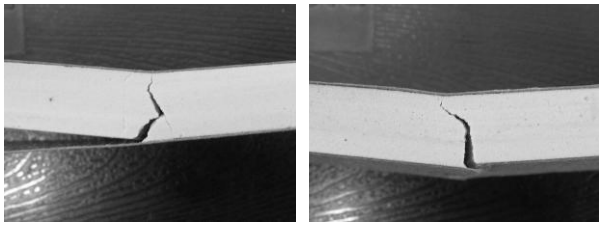


Fig.6 Estimated flexural strength based on Eq. (2) for sandwich composites for different starch contents in adhesive contained in skin paper. The zero starch content is for syntactic foam core only without skin paper. The error bars indicate 95% confidence intervals.

The mechanical performance under three-point flexural loading for the sandwich composites is summarized in Table 4 in terms of load carrying capacity (= first peak load /width) and stiffness. Two different syntactic foam core types, SL75WS50 and SL300WS30, were chosen for the sandwich composites, given that the two types have a common starch volume fraction of 0.04 and hence similar mechanical properties (Table 1) but different surface conditions due to different microsphere sizes. Flexural load carrying capacity (Table 4) appears to increase with increasing starch content in adhesive for both SL75WS50 and SL300WS30, indicating that adhesive bonding between syntactic foam core and skin paper increases for large starch content in adhesive. However, effective stiffness (EI/b) is marginally affected as expected from similar moduli for syntactic foam core and skin paper, and also as expected from negligibly small volume fraction of starch adhesive in sandwich composites. Given that the elastic moduli of skin paper and syntactic foam core are similar (Table 2), estimation using Eq. (2) for flexural strength for sandwich composites as homogeneous materials was conducted and shown in Fig.6 including syntactic foam core without skin paper on, allowing us to see the skin paper reinforcement effect as well on mechanical properties of syntactic foam core. Substantial enhancement on flexural strength up to 40% due to skin paper, depending on starch adhesive content in the skin is seen.



(a) (b)

Fig.7 Examples for delamination after fracture under three point flexural loading: (a) SL75WS50-WS70, fully delaminated; and (b) SL75WS50-WS14, least delaminated.

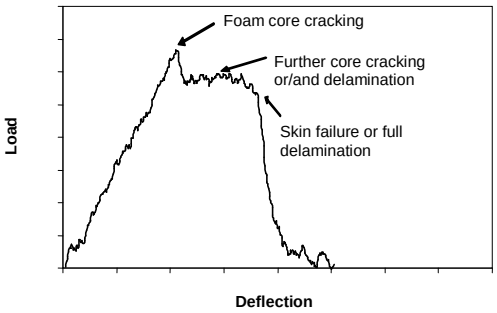
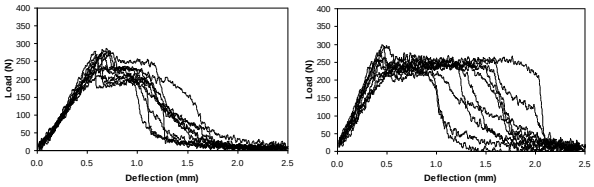


Fig.8 Schematic for different stages of failure/damage process.



(a) (b)

Fig.9 Load-deflection curves from three-point flexural testing on sandwich composites for 30/1 water/starch ratio in interface between syntactic foam core and skin paper: (a) SL300WS30-WS30; (b) SL75WS50-WS30.

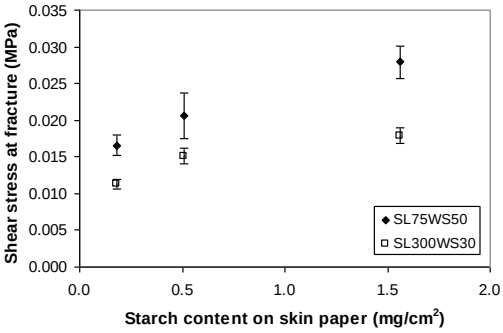


Fig.10 Shear stress on interface between syntactic foam and skin paper calculated using Eq. (7) for different starch content on skin paper. The error bars indicate 95% confidence intervals.

As for failure sequence of a sandwich composite, three different failure sites such as core, skin, and interface between core and skin may be considered and hence six permutations of failure sequence are possible. The sequence depends upon constituent properties, loading conditions, sandwich dimensions such as thicknesses of core and skin. If a span length of sandwich specimen under three point flexural loading is long, delamination of skin paper is less likely because less shear stress exerts on interface. If thickness of sandwich panel is small, delamination of skin paper is also less likely for the same reason. In experiment, we were able to detect the first audible 'pop' sound from the syntactic foam core cracking prior to any failure. Thus, the failure sequence is narrowed down from six to two possibilities of sequence i.e. core → skin → interface, and core →

interface → skin. An example of failure shown in Fig.7(a), though, indicates core → interface only, leading to full delamination without skin failure. When starch content is high in interface and hence high interfacial adhesion strength as shown in Fig.7(b), failure sequence would tend be core → skin → interface. As such, different stages of damage may be schematically described in Fig.8 based on the observation and discussion herewith. The syntactic foam core cracking first occurs at the first peak, further core cracking or/and delamination occurs in relatively flat region, and finally skin paper failure or full delamination of skin paper from syntactic foam core occurs. Experimentally obtained load-deflection curves superimposed together for sandwich composites (SL300WS30 and SL75WS50) under three-point flexural loading for 30/1 water/starch ratio in skin paper are given as examples in Fig.9. In general, energy absorption (area under the curve) is much greater for sandwich composites compared to those of syntactic foam core (see Fig.3). The energy absorption was observed to be due to damage in the form of mainly delamination of skin paper off syntactic foam core. Full delamination (Fig.7(a)) of skin paper on tensile side for some SL300WS30-WS70 and SL75WS50-WS70 was taken place but not for others with higher starch content in adhesive between syntactic foam core and skin paper. It was found that four in ten SL75WS50-WS70 specimens, and seven in ten SL300WS30-WS70 specimens were delaminated, indicating syntactic foam core SL75WS50 (small microsphere) had a relatively good adhesion with skin paper probably because of naturally smooth surface of small microspheres requiring small amount of adhesive to achieve a good adhesion. It is noted that sandwich composites with high starch content on skin paper such as SL300WS30-WS14 and SL75WS50-WS14 have relatively low damage due to less delamination (Fig.7(b)). Since delamination on tensile side is due mainly to shear stress on the interface between syntactic foam core and skin paper, the shear stress was estimated using Eq.(7), given that similar moduli of skin paper and syntactic foam core, and is given in Fig.10. As expected, shear stress increases with increasing starch content in interface between syntactic foam core and skin paper, and is high for SL75WS50 (small microsphere) syntactic foam core, supporting that syntactic foam core SL75WS50 (small microsphere) had a relatively good adhesion with skin paper.

8. Conclusions

Novel sandwich composites made of syntactic foam core, paper skin, and starch adhesive for interface between syntactic foam core and paper skin, were fabricated by varying starch content in adhesive for interface. Two different microsphere size groups (SL75 and SL300) were employed for syntactic foam core manufacture. Mechanical behaviour of manufactured sandwich composites in relation with properties of constituent materials has been studied. Properties of skin paper with starch adhesive on have been found to be affected by drying time of starch adhesive. Skin paper has contributed to increase up to 40% in estimated flexural strength over syntactic foams depending on starch content in adhesive between syntactic foam core and paper skin. Small microsphere size group (SL75) for syntactic foam core has been found to be advantageous in strengthening of sandwich composites for a given starch content in adhesive. This finding is in agreement with calculated values of estimated shear stress at interface between paper skin and foam core. Failure process of sandwich composites has been discussed in relation with load-deflection curves.

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