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SHEAR STRENGTH OF DIFFERENT CONNECTION AND CONCRETE TYPES FOR TIMBER CONCRETE COMPOSITES (TCC)

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ABSTRACT: Timber Concrete Composite (TCC) is a sustainable system that presents increasing potential for utilisation in construction. Bonding the timber and concrete is one of the most essential aspects of TCC. Hence, this research aims to investigate the shear performance of various innovative connections for TCC. Moreover, in order to increase the environmental 'friendliness' of the novel TCC system, fly ash was utilized to partly substitute Portland cement. A new kind of bonding method; micro-notch connection, for which continuous shear is transferred by interlocking with micro-notches and additional fasteners are not needed, was investigated. Furthermore, to mitigate shrinkage and cracking caused by hydration process of concrete in early ages, Superabsorbent Polymers (SAP) were introduced as internal curing agent in concrete. Overall 15 types of samples, including 45 specimens were tested, and slip modulus and connection shear strength were determined from push-out test. Performance of different connection types (nails, adhesive and micro-notches) for different configurations and using different concretes (reference concrete, FA concrete and SAP concrete) were compared. During the course of this study, it was established that workability of concrete has huge influence on TCC connection. Concrete with higher workability fully fills into timber grooves, which leads to timber and concrete notches combine tightly. Furthermore, epoxy resin has adequate strength to bond timber and concrete and shear strength of adhesive connection depends on the concrete strength. On the other hand, usage of concrete mix of high plasticity impairs the combination between wet concrete and adhesive. Finally, it was determined that micro-notch connection with slope zigzag notches can effectively link the two components of TCC and transfer the shear force through their interlocking without other fasteners. Moreover, shear strengths for such connections are much higher than for nails connectors, reaching that of adhesive connections.

KEYWORDS: Timber Concrete Composite, Micro-notch connection, Connection shear strength, Superabsorbent polymers (SAP), Fly ash concrete

1. INTRODUCTION

In recent years, due to sustainability trends in construction industry, there is potential for Timber Concrete Composite (TCC). TCC is a construction composite system that consist of a timber beam which is connected with concrete slab by various connectors [1]. It was invented in 1900s, and in 1922, Muller registered a patent for the new component [2]. During World Wars I and II the large amount of steel was used for their purposes and resulted in a shortage of steel for reinforcement in concrete, which initiated the development of TCC solution in Europe [3]. TCC has wide spectrum of applications for upgrading of existing timber floors and bridges, and construction of new buildings [4]. As a composite, TCC has many advantages over homogenous materials [5]. In this element, timber, which tensile strength is higher than that of concrete, carries the tensile stress and concrete carries compressive stress. Due to relatively high stiffness of concrete, TCC beams present less deflection and are less susceptible to vibrations when imposing loads than timer elements alone Due to the lightness of timber, TCC beams have lower self-weight than concrete ones [6]. Therefore, TCC structures transfer less load to foundation and are easier to implement than reinforcement concrete at construction site. Moreover, TCC possess, at least partly, advantages of timer environmental friendliness. Timber can absorb from 0.8 to 0.9 tonnes of carbon dioxide per cubic meter during life cycle, while production of concrete results in release of 1.1 tonnes of carbon dioxide per cubic meter [7]. Therefore, exchanging concrete to timber leads to a total saving of about 2 tonnes carbon dioxide released to atmosphere per one cubic meter of material.

As an out of plane load bearing element, significant stresses exist in the interface of timber and concrete in TCC [8]. Hence, it is necessary to properly connect the two materials and make them work together. Now the most popular connections are shear connectors (nails, bolts, and other fasters). To transfer the load between timber and concrete epoxy adhesives also can be used, which can be simpler, stronger and more economical [9,10]. Furthermore, a new kind of bonding method; micro-notch

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connection has potential for application in future [11]. For micro-notch, continuous shear transferred by interlocking with micro-notches and additional fasteners are not needed. Therefore, it can be potentially more effective and easier for implementation than other connections. However, due to its complexity and variations (shape, material types and their grades), information on its compressive behaviour is needed before general application. This project tries to provide initial technical data for this novel approach.

The hydration process of concrete in early ages is associated with autogenous shrinkage that leads to cracking, which seriously reduce its strength and durability. Such micro-cracked concrete can significantly impair the connection between components in TCC. One of the most effective methods to minimise the defects due to this process is introducing the Superabsorbent Polymers (SAP) as internal curing agent in concrete. SAP is a cross-linked polymer material with a very high liquid absorption capacity [12]. Its internal spatial network structure can absorb and store moisture, and its particles act as "water reservoirs" inside the concrete. During hydration of concrete, these "reservoirs" releasing the water gradually to support the hydration process leading to form denser and more homogeneous CSH matrix, mitigating the autogenous shrinkage and cracking [13]. This project not only studies connections TCC performance itself, but also tries to provide solution to improve concrete mechanical performance by utilizing fly ash (FA). FA is a kind of off-white powder which is waste generated in coal-burning power generation [14]. FA disposal can be harmful and by utilizing it as supplementary cementitious material the limited demand for clinker production can be achieved.

2. MATERIALS AND METHODOLOGY

2.1 CONCRETE MIX

In this study, the concrete C30 defined by *Code for design of concrete structures GB GB50010-2010* [14] was used for production of TCC samples. Its composition was designed in accordance with *JGJ 55-2011*[15]. The compositions of mixes; reference concrete, FA concrete and SAP FA concrete, are presented in Table 1.

Table 1: *Concrete mix composition per 1 m^3*

	Water (kg)	Cement (kg)	Fly ash (kg)	SAP (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
Reference concrete	205	418	0	0	613	1164
FA concrete	205	292.6	125.4	0	594.7	1130
SAP FA concrete	205	291.9	125.4	0.7	594.7	1130

The strength class of the ordinary Portland cement used in this research was 42.5 defined by *General Portland Cement GB175-2007* [16]. River sands and crushed rock were used for fine aggregates and coarse aggregates respectively. The Particle size distributions are presented in Figures 1 and 2. Tap water was used to mix concrete. FA used in this project which was produced in Henan province and its main components are SiO_2, Al_2O_3, FeO and Fe_2O_3. The SAP produced by Kexinde company with the water-absorbing capacity over than 600g per 1g of SAP within 36 seconds in deionized water. The main chemical components are low cross-linked sodium polyacrylate (88%). For SAP FA concrete, the SAP dosage should be under 0.5% to prevent reduction in compression strength according to the previous studies [17-19]. Therefore, the SAP concrete has additional SAP of 0.25 % by mass of the cement.

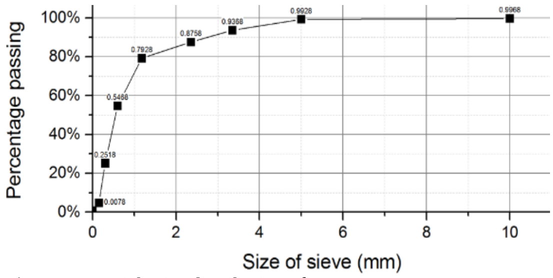


Figure 1*: Particle size distribution of coarse aggregate*

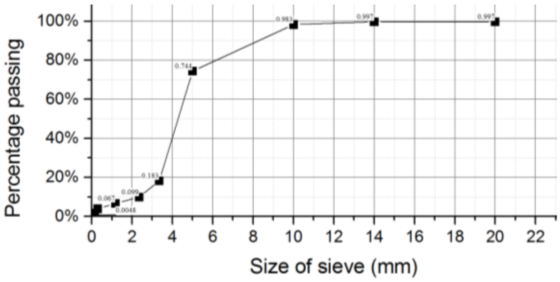


Figure 2*: Particle size distribution of coarse aggregate*

2.1 TIMBER

In this project larch from the northeast of China was used. According to *code for design of timber structure GB 50005—2003* [20], its strength grade is TC17B, for which design values (f_d) of the bending strength (f_m)is 17 MPa, the elastic modulus (E) is 10000 MPa, compressive strength parallel to grain (f_c) is 15MPa, tensile strength parallel to grain (f_{t0}) is 9.5MPa, and shear strength parallel to grain is (f_V)1.6MPa.

2.3 TCC SPECIMEN

3 kinds of connections: nails connector, adhesive connection and micro-notch connection were used in this research. The size of specimen is presented in Figure 3. The nails used in this research are normal carbon steel nails with 5cm length and 3.2 mm diameter. Position of the nails is presented in Figure 4. For adhesive connection, epoxy resin was used to glue the timber and concrete. When manufacturing adhesive connection, two components (adhesive and hardener) of epoxy resin were mixed with volume ratio 1:1 and then were applied as a one-millimetre thickness layer on timber. For the micro-notch connections, specimens with 5 different grooves patterns were manufactured and their shapes and dimensions are presented in Figure 5. The timber part was not only the component of specimen, but also the component of mould. The wet concrete was poured into moulds and then moulds were put on the vibration table for 120s to compact concrete.

15 types of samples were designed for the purpose of this

project, labelled; N-N, S-S, S-F, A-N, A-S, A-F, MSU10-N, MSU10-F, MSU10-S, MSU15-N, MR10-N, MR10-F, MR10-S and MR15-N respectively. The letter(s) before "-" represent(s) the type of connection, where "N" nails connector, "A" adhesive connection, "MSU" up slope micro-notch connection, "MSD" down slope micro-notch connection, "MR" rectangular micro-notch connection; the further number indicates the spacing distance in mm between centres of each notch; the letter after "-" means type of concrete, where "R" reference concrete, "F" FA concrete and "S" SAP FA concrete.

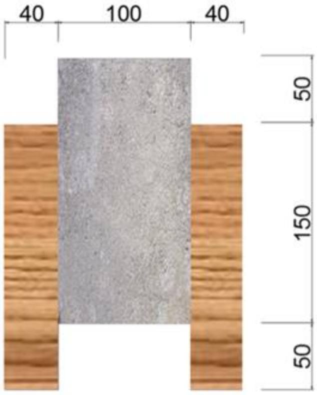


Figure 3: *Sketch of specimen*

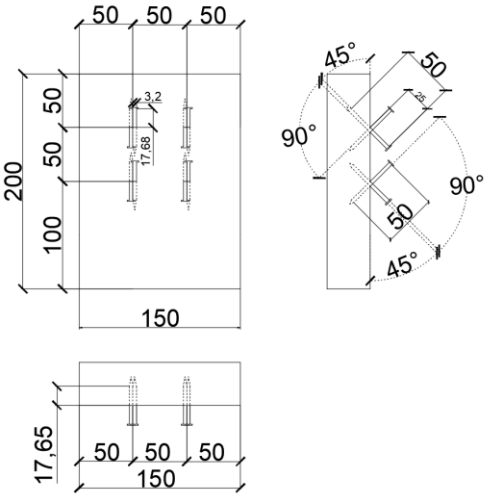


Figure 4: *Position of nails (unit of length: mm)*

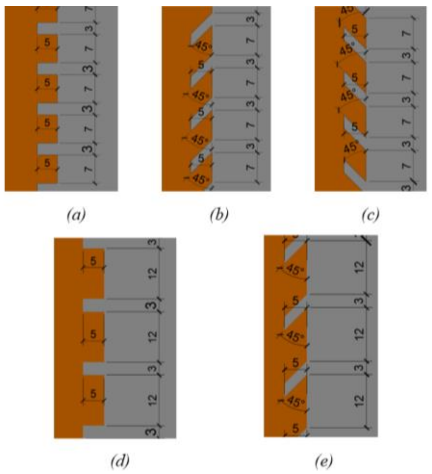


Figure 5: *Sketch of micro-notch (a) MR10 (b) MSU10 (c) MRD10 (d) MR15 (e) MSU15.*

After 24 hours, under plastic covered, the specimens were demoulded and placed in curing chamber (20 ° C and 90% RH) for a 28-day-curing.

2.4 TESTING

Compressive testing machine was used to carry out the pushout test to assess shear strength and stiffness of connections. Specimens were loaded with constant displacement to obtain failure in 5min$\pm$2min. For nails connector, due to the relative high ductility of nails, loading rate was increased after the peak load to observe nails yielding until the timber and concrete slipped away. Based on these data, the stiffness and shear strength were calculated by using equations 1 and 2.

$$E_s = \frac{\frac{1}{2}F}{d} \qquad \text{(eq. 1)}$$

where,

Es is slip modulus,

F is compressive load

d is displacement between timber and concrete components.

$$f_v = \frac{F}{A} \qquad \text{(eq. 2)}$$

where,

fv is shear strength,

A is areas between concrete-timber contact surface.

3. TEST RESULTS AND ANALYSES

3.1 TEST RESULTS

3.1.1 Concrete

3 concrete specimens with the same size as concrete part of TCC specimens for each type of concrete were tested in compression. The compressive strength and their standard deviations and slump result valves of 3 kinds of concrete are shown in Table 3.

Table 3*: Test result of concrete*

Concrete number	*Reference concrete*	*FA concrete*	*SAP FA concrete*
Average compressive strength (std) (MPa)	*24.69 (1.82)*	*24.48 (0.23)*	*22.42 (0.81)*
Slump (mm)	*13*	*156*	*86*

The compressive strengths of reference concrete, FA concrete and SAP FA concrete were 24.69MPa, 24.48MPa and 22.42MPa, respectively. For the SAP concrete, compared to FA concrete, the compressive strength was reduced by 8.4% and this valve was further reduced by 9.2% when it was compared to reference concrete.

The slump values of reference concrete, FA concrete and SAP FA concrete were 13mm, 156mm, 86mm. Due to the relatively high-water absorption by SAP the slump of SAP FA concrete was much lower than for FA concrete. The slump of reference concrete was low, indicating that the workability was limited. It was observed that the reference concrete did not fully fill the moulds and for micro-notches, despite vibrations on shaking table for 2mins. However, this phenomenon was not observed for FA concrete and SAP FA concrete, which indicates that FA can improve the workability of concrete.

3.1.2 Push-out test

Testing results for 45 specimens are presented in Table 4.

***Table 4**: Push-out test results*

	Shear failure occurred position	*Mean valve of slip modulus*		*Mean value of shear strength*	
		Valve (kN/mm)	*std*	*Valve (N/mm2)*	*std*
N-R	*Timber*	*6.2*	*0.2*	*0.35*	*0.01*
A-R	*Concrete*	*50.4*	*2.1*	*0.95*	*0.07*
MSU10-R	*Both notches*	*32.6*	*23.2*	*0.62*	*0.07*
MSU15-R	*Concrete notch*	*62.7*	*13.6*	*0.85*	*0.10*
MSD10-R	*Both notches*	*82.9*	*6.7*	*1.15*	*0.10*
MR10-R	*Concrete notch*	*10.8*	*1.5*	*0.48*	*0.16*
MR15-R	*Concrete notch*	*14.7*	*3.5*	*0.23*	*0.02*
N-F	*Timber*	*6.7*	*0.9*	*0.43*	*0.05*
A-F	*Concrete*	*75.8*	*11.5*	*1.02*	*0.40*
MSU10-F	*Both notches*	*54.4*	*28.3*	*0.95*	*0.24*
MR10-F	*Concrete notch*	*31.9*	*8.6*	*0.53*	*0.04*
N-S	*Timber*	*7.3*	*0.6*	*0.36*	*0.02*
A-S	*Concrete*	*46.8*	*15.1*	*1.06*	*0.07*
MSU10-S	*Both notches*	*35.6*	*15.1*	*0.68*	*0.13*
MR10-S	*Concrete*	*15.8*	*6.3*	*0.20*	*0.05*

The shear strengths for nails connector of reference concrete, FA concrete and SAP FA concrete are 0.35MPa, 0.43MPa and 0.36MPa, respectively. Adhesive connection has relative high shear strength, the average shear strengths for three kinds of concrete were 0.95MPa, 1.02MPa and 1.06MPa for reference concrete, FA concrete and SAP FA concrete, respectively. For rectangular micro-notch, the strength of reference concrete with 10mm gap was 0.48MPa and the FA concrete increased the shear strength which was 0.53MPa. However, SAP did not have positive influence on the connection shear strength which was only 0.20MPa.

It was observed that nails connector did not break immediately when the slip between timber and concrete occurred, since nails did not break at all during the testing. Other connections behaved in brittle manner. Moreover, for the rectangular notch specimens the broken concrete notches were embedded into the timber grooves while the timber notches kept complete.

3.2 ANALYSES

3.2.1 The influence of type of concrete on connections

The force-displacement curves for the same connection were plotted, see in Figure 6.

Reference concrete with the lowest workability achieved the highest shear strength. On the contrary, FA concrete whose workability is the highest of all 3 types of concretes had limited shear strength when it was used for adhesive connection specimens. It might be due to the fact that the high flowability of wet FA concrete washed off the adhesive layer. Vibration can only enhance this phenomenon. However, FA can improve the rectangular micro-notch connection. This might be caused by the relatively high workability of concrete which results in filling completely timber notches. And for nails connector, there are not huge differences among the 3 types of concrete. Moreover, the nails connector specimens for FA concrete show the slightly higher performance than for the others in this

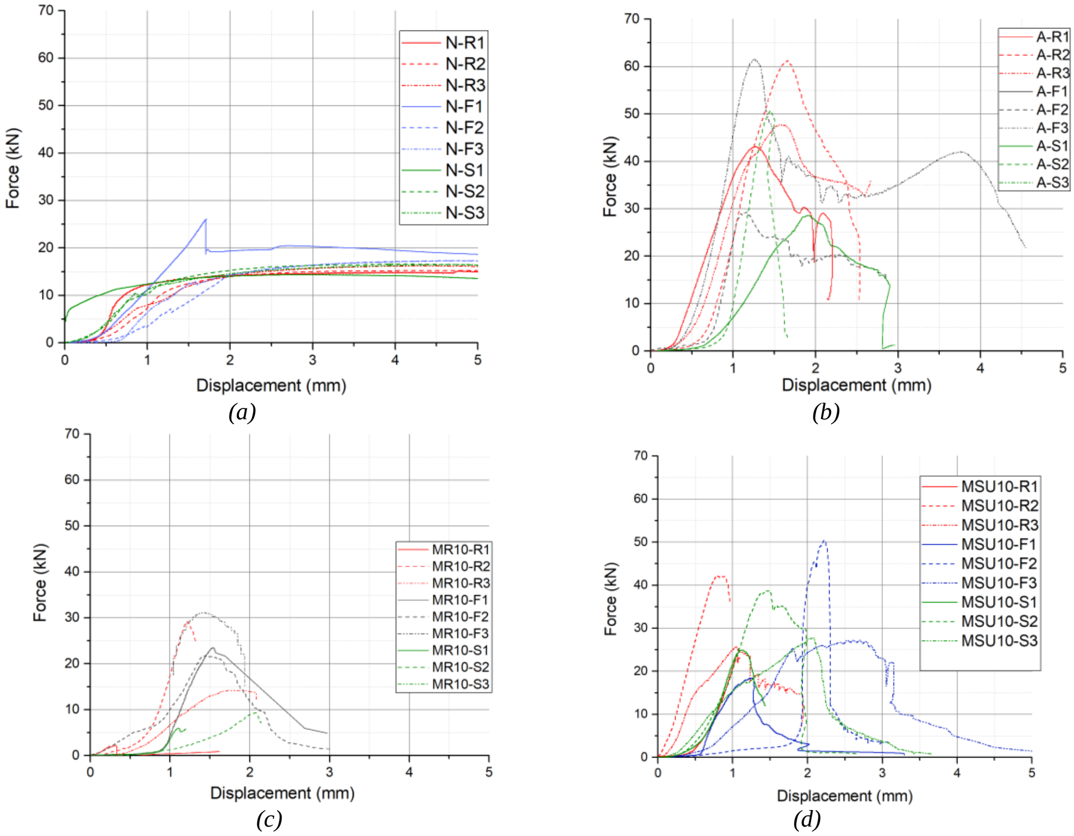
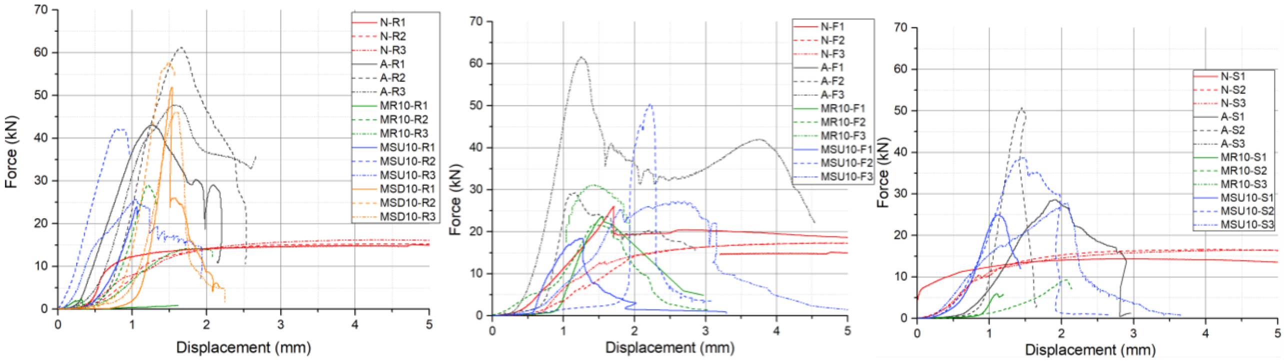


***Figure 6**: Force-displacement curves (a) nails connector, (b) adhesive connection, (c) and (d) micro-notch connection.*

research. It might be because the FA concrete has higher friction on the contact surface between timber and concrete element due to existence of FA particles. On the one hand, SAP decreased the compressive strength and workability, which have negative effects for connections. On the other hand, it could mitigate the cracking and shrinkage, which is beneficial for connection, especially for micro-notch connections. It might be a reason for the fact that the mean value of shear strengths of reference concrete and SAP concrete were similar.

3.2.2 The influence of type of connection on its shear performance

It was observed, see Figure 7. that nails connector has much lower shear strength than adhesive connection and slope micro-notch connection. Moreover, the slip modulus of nails connector is the lowest, while adhesive connection and slope micro-notch connection have similar shear strength and slip modulus. Nails connector has the smallest standard deviation and the force-displacement curves also show similar trend. For the adhesive connection specimens, the failure always happened on the concrete part. Hence, increasing the shear strength of concrete can increase the shear strength of whole adhesive connection. For the down slope micro-notch, the value of shear is the highest among specimens for reference concrete, and Table 4 shows, the average shear strength could reach up to 1.15MPa. This might be associated with the friction between timber component and platform in the push-out test that cannot be ignored. When the down slope micro-notch connection specimens were under loading, the horizontal force component exists. While the friction linked with a horizontal constraint would prevent the horizontal displacement. What is more, the failure only happened on concrete notches and on timber notches failure was not observed.



(a) (b) (c)

***Figure 7**: Curves of force-displacement (a) reference concrete. (b) FA concrete. (c) SAP.FA concrete*

3.2.3 Discussion of length of gaps on connection

For rectangular micro-notch connection spacing had significant influence on results, see Figure 8. For spacing with of 15mm higher strength were recorded than gaps with 10mm.

Moreover, as indicated by the broken sections, it can be found that for both 10mm and 15mm notches spacing failure was in concrete notches and the timber notches were kept intact. Therefore, increasing the thickness or multiplying the number of concrete notches will increased the shear strength of the rectangular micro-notch connection.

For the up slope micro-notch connection, see in Figure 9 strength of up slope micro-notch with 10mm spacing is slightly higher than for 15mm and as Table 4 shows the mean value of shear strengths are 0.62MPa and 0.83MPa. From the broken section which is shown in Figure 10, it can be found that failure only happened on concrete notches for the spacing of 15mm, while percentage of failure happened in timber notches is higher than concrete notches when the gap is 10mm. Gaps with 15mm length have the higher strength than that of 10mm-long-gap connection. Therefore, the highest shear strength of the connection, for micro-notch sizes from this study, should be for the spacing between 10mm and 15mm.

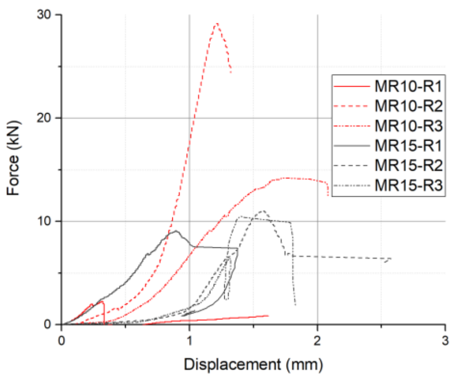


***Figure 8:** Force-displacement curves of rectangular micro-notch with 10mm and 15mm gaps.*

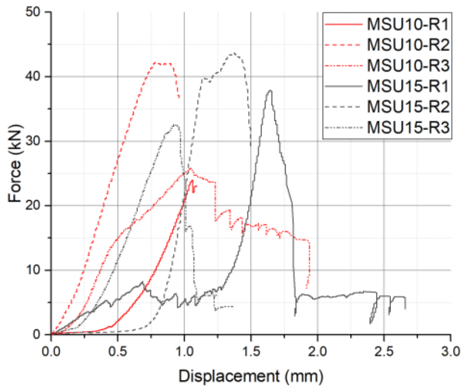


***Figure 9**: Force-displacement curves of up slope micro-notch with10 mm and 15mm gaps*

4. CONCLUSIONS

Based on investigations presented in this study, the following conclusions can be formulated:

- Workability of concrete has huge influence on TCC connection. Concrete with higher workability fully fills timber grooves which allows to timber and concrete notches combine tightly. However, it can impair the bonding between concrete and adhesive.
- SAP addition to concrete had insignificant influence on performance of TCC connection. Even though, SAP decreased compressive strength and workability, which is impaired for connections, it could mitigate the cracking and shrinkage, which is beneficial for connection, especially for micro notch connection.
- For nails connector in this research, the strength mainly deepened on the performance of nails. Due to the high ductility, two sides of specimen were kept together in push-out test.
- Adhesive connection has relatively high strength and slip modulus. In this study failure always happened on concrete component. Hence, increasing the strength of concrete can increase the shear strength of whole adhesive connection.
- The shear strength of rectangular micro-notch connection was relatively low in this study. However, the slop micro-notch connections had high shear strength, even similar with that of adhesive connection.

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