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Effect of concrete modification on shear of connections for timber–concrete composites

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Timber–concrete composites (TCCs) take advantage of the properties of timber and concrete simultaneously. TCC slabs consist of timber beams or a timber deck, which resist tensile and bending stresses, connected through different types of shear connectors to an upper concrete slab, which withstands compressive stresses. The stiffness and strength of the slab are mostly defined by the properties of the connectors. To avoid the use of external materials that could be environmentally harmful, micro-notch connections were tested. These micro-notch connections are notches cut into timber elements and filled with wet concrete. The research focused on the influence of the gap between the micro-notches, the experimental configuration, the concrete composition and the concrete curing process on the shear strength of the connectors. The concrete compositions included ground granulated blast-furnace slag (GGBS) and superabsorbent polymer (SAP). These additives were used to evaluate their compliance with the shear strength of the TCC connections. GGBS was used to reduce the cement content in the concrete mix and SAP was used as a water-entraining agent to reduce the autogenous shrinkage of the concrete.

Notation

A	total area of connector
E_d	elastic modulus of timber
F_{max}	maximum compressive load applied to specimen
$f_{c,0,d}$	compressive strength along grain of timber
$f_{t,0,d}$	tensile strength along grain of timber
$f_{v,d}$	shear strength of timber
M	bending moment
R_S	shear strength of specimen
α	angle between the connector of an asymmetrical shear test specimen and the horizontal

1. Introduction

In the face of various environmental challenges, the civil engineering industry is increasingly exploring different ways to improve building materials and make them more environmentally friendly while maintaining satisfying mechanical properties.

Concrete is the most widely used construction material in the world and is made of a mixture of gravel, sand, water and cement. Sand and gravel are now the most (over)extracted materials in the world, while cement production generates more carbon dioxide emissions than any other industrial process. Cement clinker production contributes about 4% of global total carbon dioxide emissions from fuel use and industrial activities. To address sustainability, great improvements have been made to make concrete more environmentally friendly while meeting mechanical performance requirements (Lemay and Lobo, 2011). These improvements include the utilisation of waste materials as cement replacements (e.g. fly ashes and ground granulated blast-furnace slag (GGBS)) and recycled aggregates.

Wood is the only construction material that stores carbon dioxide through photosynthesis. Timber products lock in approximately 1 t of carbon dioxide per cubic metre of wood. In addition, timber has a very high strength-to-weight ratio and its strength performance makes it suitable for a wide range of structural applications.

Timber–concrete composites (TCCs) have not been investigated in the past from a sustainability perspective, but rather as an alternative to reinforced concrete thanks to the clever collaboration between the two materials. After World War II, steel shortages led to the use of timber to resist the tensile stresses originally withstood by steel reinforcing bars (Dias, 2005; Lemay and Lobo, 2011). So far, TCC systems have been used in different structural applications such as bridge decks, multi-storey buildings and the renovation of old timber floors.

TCC structures exploit the composite action between a concrete slab and timber elements (timber beams or a timber deck). The concrete slab and the timber elements or slab, made of cross-laminated timber (CLT) for example, are joined by shear-resistant connectors. The mechanical behaviour of the composite structure mainly depends on the strength and the stiffness of the connectors (Yeoh *et al.*, 2011). If the connectors are stiff and have a high resistance to shear stresses, the whole structure will benefit from a high (ideal) composite action: the timber will withstand tensile stresses due to bending while the concrete will resist compressive stresses (full composite action). If the connectors have low stiffness or strength resistance to shear stresses, the concrete layer and the timber layer move independently of each other. The cross-section will then have two individual neutral axes, so that discontinuous bending strain at the interface will occur (no composite action).

There are many advantages in utilising TCCs in multi-storey buildings. TCCs make up for a few weaknesses of timber structures by reducing their susceptibility to vibrations and excessive deflection and enhancing their resistance to fire and acoustic separation (Ceccotti, 1995). The connection of a concrete slab to a timber element will also allow for larger spans with reduced mass in comparison with a traditional concrete slab, so seismic action is limited. In the case of a pre-installed timber slab, the cost of the formwork is greatly reduced because the timber slab itself acts as permanent formwork for the concrete slab. In addition, TCC structures are promising solutions for the refurbishment of old structures as well as in new constructions (Auclair *et al.*, 2016; Balogh and Gutkowski, 2008; Balogh *et al.*, 2008; He *et al.*, 2016).

The main aims of this study were to

- perform experimental tests on different TCC specimens in order to assess the shear strength of different notched connectors
- evaluate the effects of the micro-notch pattern and configuration (length of the gaps between the notches) on the connection strength
- evaluate the effects of the addition of superabsorbent polymer (SAP) to the concrete mix on the mechanical properties of the connections
- evaluate the effects of the addition of GGBS in the concrete mix on the mechanical properties of the connections
- evaluate the suitability of two different testing configurations for the mechanical characterisation of TCC connections (push-out tests and asymmetrical shear tests)
- evaluate the effects of the curing process on the connection efficiency and assess the impact of the concrete's internal curing.

2. Parameters of interest for TCC connectors

2.1 Type of connector

Various connector designs have already been tested by researchers worldwide (Yeoh *et al.*, 2011). The large majority of studies (45%) are focused on dowel-type fasteners (Dias *et al.*, 2018). Notches and notches combined with steel fasteners represent together approximately 33% of the studies. These two types of fastener together represent more than 75% of the relevant scientific research found in the literature. Other connection systems include a wide range of connectors such as steel planes, nailplates, systems based on gluing or systems based on friction; overall, these represent about 22% of the studies. Glued connections are known to have a particularly high resistance to shear stresses (Miotto and Dias, 2011) but their use is not encouraged as their application on site is complex and their production is highly toxic with a high carbon dioxide footprint (Lemay and Lobo, 2011). Notched connections can be obtained either through drillings in the timber member, cut-outs in the timber members or through glued blocks on the structural timber member. The first two approaches are usually taken due to their greater simplicity and lower cost. Notched connections are very effective, with an excellent balance between simplicity and mechanical performance, particularly with respect to stiffness (Dias *et al.*, 2018; Van der Linden, 1999).

Micro-notches are small cuts made into the timber that are designed to be filled with concrete. The cuts are made across the width of the timber boards and are spaced regularly. These micro-notches do not exceed a few millimetres in size. When the concrete is poured, it fills the empty spaces in the notches and hardens during the curing process. However, micro-notches are still very seldom used in composite slabs and, so far, very little research has been carried out on micro-notches in TCCs.

Strengthening connectors by means of screws or any metallic fasteners fastened on site makes up a large part of the cost of the overall TCC and therefore an all-wood prefabricated micro-notched connector is better from an economic point of view. In addition, their sustainable impact is undeniable as no other external material is used in the design of these connector.

Three types of connectors were studied in this work (Figure 1). These were

- micro-notch connections with a 15 mm spacing between the notches
- micro-notch connections with a 20 mm spacing between the notches
- an epoxy adhesive connection.

The micro-notch connections were 4 mm wide and 5 mm deep, and were inclined in the opposite direction to the relative displacement of the concrete and the timber.

2.2 Concrete admixtures

2.2.1 SAP and internal curing

SAPs are natural or synthetic three-dimensional cross-linked polymers or copolymers with a high capacity to absorb fluids

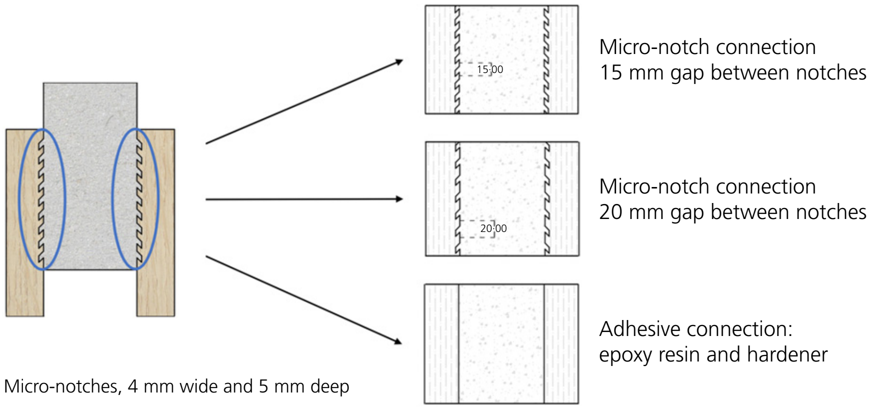


Figure 1. The three types of connectors studied

(De Belie *et al.*, 2018). The swelling capacity depends on the nature of the monomers and the cross-linking density (Kabiri *et al.*, 2003), but can be as high as 1000 g/g (Gibas and Janik, 2010). More and more research is being focused on the use of SAPs in mortar and concrete (Klemm and Sikora, 2013; Sikora and Klemm, 2012, 2014, 2015). SAPs were introduced as internal curing agents in cementitious systems with a low water/binder ratio to reduce the self-desiccation shrinkage during hardening (Klemm and Sikora, 2012; Klemm *et al.*, 2013; Mechtcherine, 2016). SAPs can also be added to cementitious materials to increase their freeze–thaw resistance (Cusson *et al.*, 2012; Mechtcherine *et al.*, 2017) and induce self-sealing and self-healing effects (Mignon *et al.*, 2017). Depending on the environment, SAPs can take two forms

- a collapsed (or dry) state, which results from the desorption of water (Figure 2(a))
- a swollen state, which results from the hydration of SAPs when they come into contact with water (Figure 2(b)).

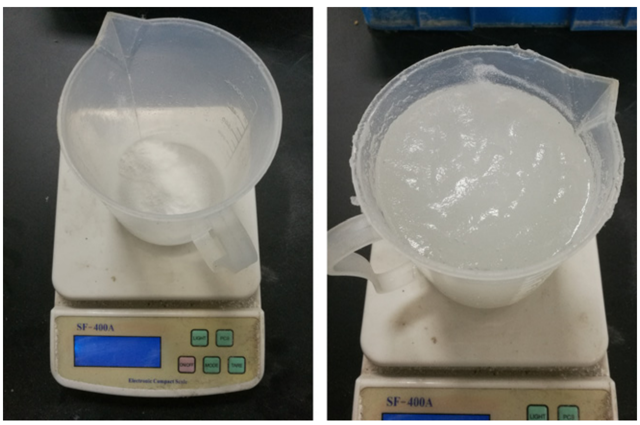


Figure 2. SAP in dry state (a) and in swollen state (b)

The most commonly used SAP is sodium polyacrylate (Dubey, 2016). As internal curing agents, SAPs play a major role in TCC technology. Concrete shrinkage creates additional stresses in the timber parts due to volumetric deformations. By releasing water during the hydration of concrete, SAPs offer the capacity to enable internal curing. During concrete mixing, SAPs absorb some of the water available in the mix and swell. Internal water reservoirs (or water-filled cavities) are thus formed homogeneously in the fresh concrete, and these serve as internal curing agents. While the concrete hardens and the hydration process is under way, the SAPs continuously release the previously absorbed water (Mechtcherine, 2016). Consequently, the self-desiccation and the autogenous shrinkage of the concrete are mitigated. However, the relationship between the amount of water available for internal curing and autogenous shrinkage still needs to be investigated in detail (Shen *et al.*, 2015).

Additionally, SAPs have been associated with improvements regarding the strength and workability of concrete (Cusson *et al.*, 2012). However, the positive impact of SAPs is still disputed, especially with regard to strength. Indeed, SAPs may create voids in their collapsed (dry) state due to the drying process, which increases the porosity of the concrete and ultimately reduces its strength (Wang *et al.*, 2009). However, by providing an additional amount of water, SAPs enhance the degree of hydration and consequently increase strength (self-healing effect) (Dang *et al.*, 2017). The dominant effect is determined by the water/cement (w/c) ratio and the amount of SAP used in the mix. For a high w/c ratio (over 0.45), the addition of SAP does not influence hydration very much, which mainly leads to a reduction in compressive strength. Conversely, SAPs may enhance strength for low w/c ratios. According to Dang *et al.* (2017), the dosage of SAP should not be more than 0·5% of the amount of cement as an addition greater than this reduces the strength of the concrete. Dang *et al.* (2017) compared the compressive strength of concrete containing SAP with a volume of 0·1% to 0·3% of cementitious materials with the strength of a reference concrete. They found that, compared with the reference concrete, the SAP had little effect on the compressive strength at an early age and a negative effect of up to 24% at medium ages (14 d), mainly due to larger voids in the cementitious matrix. At later ages (56 d), the compressive strength increased by up to 7·2% due to internal curing, while that of the reference concrete stopped increasing. Concretes with different amounts of SAP also showed lower shrinkage values at later ages (ranging from 9% to 20%) when compared with the reference concrete.

2.2.2 GGBS

Blast-furnace slag is a by-product of the steel industry and can be used as a replacement for Portland cement. Used in addition to Portland cement, GGBS does not degrade the strength of the concrete (Suresh and Nagaraju, 2015), but it is less reactive than pure Portland cement. As GGBS hardening is much slower than cement hardening, it needs to be mixed with Portland cement to be activated (latent hydraulic component). The proportion of GGBS used is in the range of 20–80% of the amount of cement in the mix. The main benefits of using GGBS are that it reduces the usage of cement and decreases the amount of waste by-products from the steel industry going to landfill.

2.3 Experimental shear testing

Various specimen configurations are used to carry out tests for the assessment of the shear strength of timber–concrete joints. Generally, they can be divided into two groups – double-shear push-out tests (symmetrical samples) (Dias, 2005; Kuhlmann and Michelfelder, 2004; Müller, 2017) and single-shear push-out tests (asymmetrical samples) (Crocetti *et al.*, 2015; Eisenhut *et al.*, 2016; Lukaszewska, 2009), as shown in Figure 3. The principle is identical for both tests: a composite specimen is placed in a compression testing machine and load is applied only on the timber or the concrete part of the specimen, so that the timber and concrete are pushed in opposite directions and shear stresses are applied on the connection. The shear strength of the timber–concrete connection can subsequently be measured until failure.

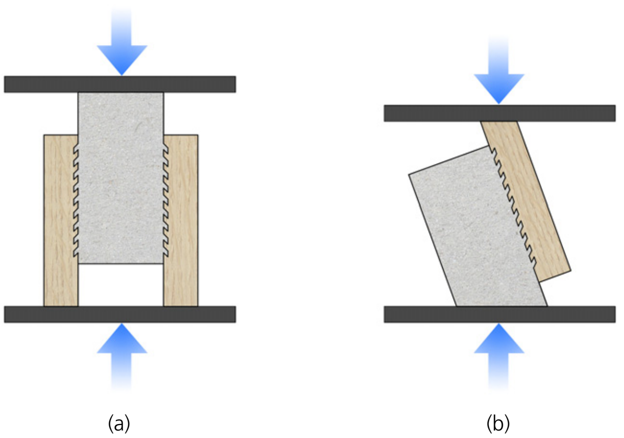


Figure 3. Principle of (a) double-shear push-out test (symmetrical sample) and (b) single-shear test (asymmetrical sample)

In double-shear push-out tests, because of symmetry, the compressive strength of the specimen can be considered equal to twice the shear strength of the connection between timber and concrete. However, as timber is a natural material, the modulus of elasticity of the two timber parts used cannot be exactly identical, which may introduce an eccentricity in the push-out test.

In asymmetrical single-shear tests, the compressive load induces compression at the timber–concrete interface, which generates friction on the interface (Crocetti *et al.*, 2015; Lukaszewska, 2009). Thus, the shear strength and slip modulus are overestimated (by approximately 10% according to Lukaszewska (2009)) because the connection's shear strength is enhanced by the friction on the interface.

3. Materials and methods

3.1 Materials

For the concrete mixtures used in this study, coarse aggregates with a maximum aggregate size of 10 mm and Portland cement (CEM I 42.5) were used with two admixtures (SAP and GGBS). The SAP was sodium polyacrylate with a water-absorbing capacity of at least 300 times its mass according to the manufacturer. However, its water-absorbing capacity is unknown for cementitious pastes. The test specimens were made of larch originating from the north-east of China. The adhesive was made from epoxy hardener and epoxy resin mixed in equal proportions. According to the manufacturer, the shear bond strength of the adhesive in steel is 12 MPa. The timber strength grade was TC17B, according to the Chinese code for the design of timber structures (GB 50005-2017 (SAC, 2017)), which ensured an elastic modulus (E_d) of 10 000 MPa, a compressive strength along the grain ($f_{c,0,d}$) of 15 MPa, a tensile strength along the grain ($f_{t,0,d}$) of 9·5 MPa and a shear strength ($f_{v,d}$) of 1·6 MPa.

3.2 Production of specimens

Three types of concrete were produced, using proportions calculated using the British Department of Environment (DoE) method (Newman and Choo, 2003). A slump of 60–180 mm was chosen in order to produce concrete with a high workability. The use of SAP induces the absorption of a certain amount of water and a high level of slump ensures that an amount of water remains available in the mix. Three types of concrete were produced: (*a*) a standard type of concrete (called 'normal concrete' in this paper), (*b*) concrete with SAP (0·25% of the amount of cement) and (*c*) concrete with GGBS (50% of the amount of Portland cement). The mix proportions of these concretes are shown in Table 1.

Table 1. Composition of the three types of concrete

	Normal concrete	Normal concrete with SAP	Normal concrete with GGBS
Free water content: kg/m^3	250	250	250
Cement content: kg/m^3	500	498·75	250
Fine aggregate content: kg/m^3	864	864	700
Coarse aggregate content: kg/m^3	736	736	596
SAP content: kg/m^3	0	1·25	0
GGBS content: kg/m^3	0	0	250

Push-out tests on both asymmetrical and symmetrical samples were designed according to the literature on experiments related to TCCs (Clouston *et al*., 2005; Crocetti *et al*., 2015; Dias *et al*., 2018; Eisenhut *et al*., 2016; Kuhlmann and Michelfelder, 2004; Lukaszewska, 2009; Miotto and Dias, 2011; Müller, 2017; Yeoh *et al*., 2011). The symmetrical push-out test specimens (see Figure 3(a)) consisted of concrete blocks of 100 mm width, 200 mm length and 150 mm depth. Two timber boards were placed on either side of the concrete block so that the base of the concrete block was higher than that of the timber boards by 50 mm. The timber boards were 200 mm long, 40 mm wide and 150 mm deep. The asymmetrical shear test configuration (see Figure 3(b)) was derived from the symmetrical push-out test configuration, with only one timber board.

The pre-assembled moulds were made from plywood boards (Figures 4 and 5). The structure of the mould was kept steady with the use of a threaded steel rod and bolts on each side and the timber boards were set in place by screws. The interior surfaces of the mould that would come into contact with the concrete were coated with oil so that the wet concrete would not stick to the mould. The moulds were filled with wet concrete and set on a vibrating table for 120 s in order to eliminate air bubbles. The specimens were demoulded 24 h after being cast. The final specimens are shown in Figures 6(a) and 6(b).

Some of the specimens were placed in a curing chamber for 28 d. So that the specimens would be constantly exposed to moist air during this time, the temperature was set at 25°C and the relative humidity was set at 90%. In order to test the effects of internal curing on the specimens containing SAP, some specimens were placed in plastic bags outside the curing chamber so that the curing process could be completed in constant conditions. These specimens were thus not exposed to the moist air in the curing chamber, so the curing process relied entirely on the additional water provided by the SAP. A group of specimens containing SAP was also placed inside the curing chamber, so that they could be compared with those cured outside the curing chamber.

In total, 13 TCC samples were designed for experimentation in order to take into account the different properties. Five specimens were produced for each type of sample so that several measurements could be made. Thus, 65 specimens were

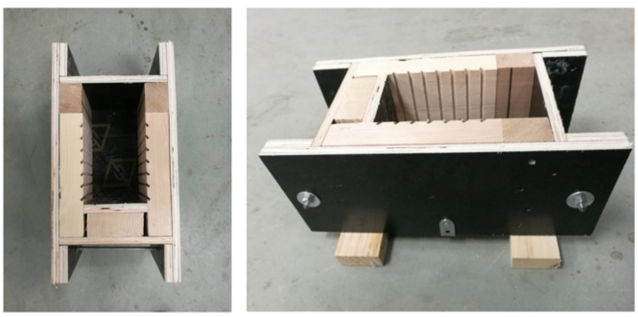


Figure 4. Mould for symmetrical specimens

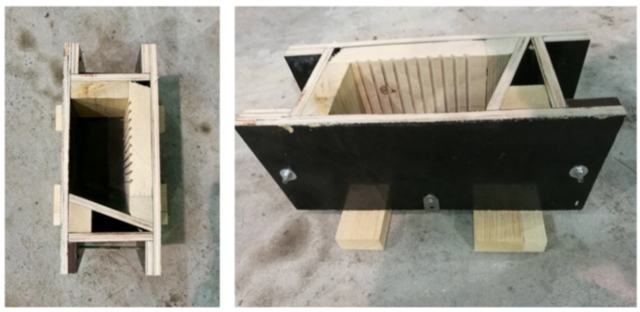
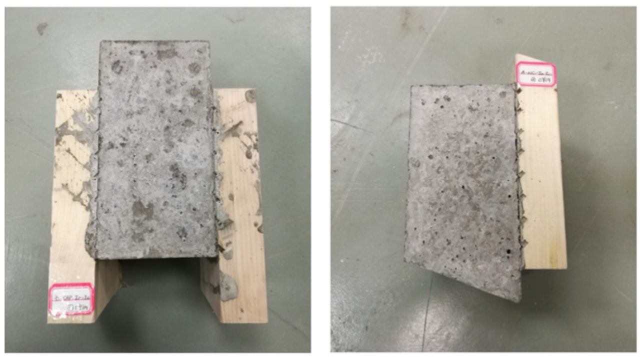


Figure 5. Mould for asymmetrical specimens



(a) (b)

Figure 6. (a) Symmetrical specimen; (b) Asymmetrical specimen

Table 2. Details of the specimen types

Type	Number of specimens tested	Configuration		Concrete type			Curing (in or out of chamber)	Type of connector	
		Symmetrical	Asymmetrical	Normal	SAP	GGBS		Micro-notch gap: mm	Adhesive
PO-NC-In-15	4	✓		✓			In	15	
PO-SAP-In-15	5	✓			✓		In	15	
PO-NC-Out-15	4	✓		✓			Out	15	
PO-SAP-Out-15	5	✓			✓		Out	15	
A-NC-In-15	5		✓	✓			In	15	
PO-NC-In-20	5	✓		✓			In	20	
PO-SAP-In-20	3	✓			✓		In	20	
A-NC-In-20	5		✓	✓			In	20	
PO-NC-In-A	5	✓		✓			In		✓
PO-SAP-In-A	5	✓			✓		In		✓
A-NC-In-A	5		✓	✓			In		✓
PO-GGBS-In-15	4	✓				✓	In	15	
PO-GGBS-In-20	5	✓				✓	In	20	

made in total. The characteristics of the tests specimens are summarised in Table 2.

3.3 Compressive (push-out) tests on the specimens

The shear strength of the connector of each specimen, regardless of its configuration (symmetrical of asymmetrical) or concrete composition, was measured using a compression testing machine. In a procedure similar to that used in other studies on connectors for TCCs (Sikora and Liu, 2018; Sikora *et al*., 2016; Xing *et al*., 2019), compressive stress was applied on the specimen until the connector failed. When the data acquisition was launched, load was applied according to a displacement of 0·5 mm/s, based on the Chinese standards GB 50107-2010 (SAC, 2010) and GB/T 50329-2002 (SAC, 2002). Failure generally occurred 4–6 min after data acquisition was launched. The data acquisition system monitored the load and displacement throughout the test. Load–displacement graphs for each specimen were drawn and used to compute the mean shear strength and the mean slip modulus of each type of specimen, according to the method and formulae detailed in Section 4.3.

Table 3. Slump test results

Concrete type	Mean slump: cm
Normal concrete	21
SAP concrete	20
GGBS concrete	19·5

4. Results

4.1 Material properties

4.1.1 Slump test

In order to estimate the workability of the concretes, slump tests were performed according to BS EN 206-1:2000 (BSI, 2001). As shown in Table 3, the three types of concrete had slump values exceeding the range predicted by the DoE method. This could be due to the low percentage of fine aggregates (passing a 600 μm sieve), which increased the proportion of fine aggregates in the mix and reduced the proportion of coarse aggregates. It could also be due to a higher amount of water in the fine aggregates, which might have resulted from an incomplete drying process.

4.1.2 Concrete compressive strength

A few observations can be made with regard to the compressive strength results shown in Table 4. The specimens cured outside the curing chamber appeared to have a lower mean compressive strength than their counterparts curing inside the chamber. In addition, the specimens made with concrete containing SAP had higher mean compressive strengths than those made with normal concrete. However, it should be noted that these observations might be imprecise, as the results showed high standard deviations. Overall, the specimens made with concrete containing GGBS showed the lowest mean compressive strength.

Table 4. Concrete compressive strength

Concrete type	Mean compressive strength: MPa	Standard deviation	95% confidence interval: MPa
Normal concrete (inside curing chamber)	23·66	5·08	(17·91; 29·41)
Normal concrete (outside curing chamber)	21·45	2·50	(18·62; 24·28)
SAP concrete (inside curing chamber)	27·22	3·69	(23·04; 31·40)
SAP concrete (outside curing chamber)	24·64	4·25	(19·83; 29·45)
GGBS concrete	20·92	0·98	(19·94; 21·90)

4.2 Failure modes

For all the micro-notched specimens, failure occurred in the concrete layer, as shown in Figure 7 (shearing of the concrete teeth). The timber parts were mostly intact after the failure, regardless of the concrete composition or the type of connection. The shape of the micro-notches did not change during the failure. For the adhesive connectors, a substratum failure occurred in the concrete, close to the interface between the concrete and the timber (Figure 8).

As the load was applied according to a constant displacement of 0·5 mm/s in the compressive testing machine, the load increased according to the slip before failure. Small cracks in the concrete layer in the vicinity of the connection appeared before failure. For a minority of the specimens, failure occurred right after cracking started; therefore, the load–slip curve decreased sharply and the test was stopped. For most of the specimens, cracking started 3–4 min after the start of the test. However, for the asymmetrical samples, the failure was always rather sudden and abrupt, with the concrete and timber parts being pulled apart at high loads (above 70 kN).

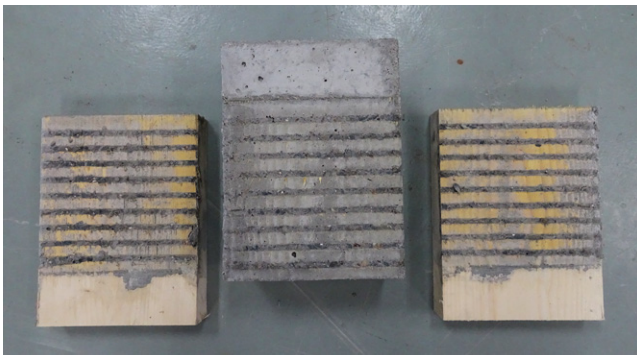


Figure 7. Failed specimen with micro-notch joints

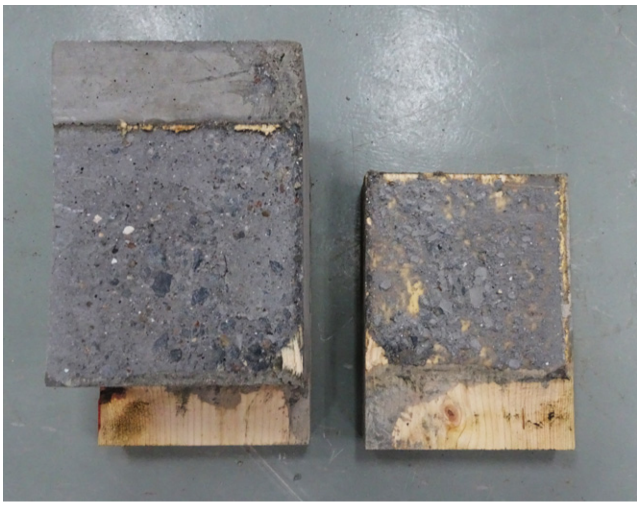


Figure 8. Failed specimen with adhesive joints

4.3 Shear strength and slip modulus

The mean shear strength was computed by calculating the mean of the shear strength of each of the five specimens for each type of sample. The shear strength (R_S) was obtained as

1. $$R_S = \frac{F_{max}}{A}$$

where F_{max} is the maximum load and A is the shear area of the connection.

The total area of the connection was 45 000 mm^2 for the symmetrical samples (both sides of the concrete block were taken into account) and 25 500 mm^2 for the asymmetrical samples. The maximum load (F_{max}) for the asymmetrical samples was not equal to the maximum load obtained in the compressive tests. The direction of the shear force applied on the connection was parallel to the direction of the connection and therefore only the component parallel to the direction of the connection was taken into account. F_{max} was thus equal to the maximum load obtained through the compressive test multiplied by $\sin \alpha$, where α is the sample inclination angle.

2. $$R_S = \frac{F_{max} \sin \alpha}{A}$$

The slip modulus was measured by taking the slope of the load–displacement curve.

5. Discussion

The values of the mean shear strength and mean slip modulus are provided in Table 5.

5.1 Effect of the type of connection

Experimental load–slip curves are presented in Figure 9 for different samples, concrete mixtures and curing conditions. The results for the adhesive samples are also plotted in Figure 9. The load–slip curves are in accordance with previous research: the adhesive joints had much higher shear strength than the mechanical joints, regardless of the type of concrete used. For the first group of specimens (symmetrical samples, normal concrete, cured inside the curing chamber), the mean shear strength of the adhesive connectors (0·87 MPa) was more than double that of the micro-notch connectors (0·38 MPa for 15 mm gaps and 0·29 MPa for 20 mm gaps) (Figure 9(a)). This was also found to be the case for the third group of specimens (symmetrical samples, SAP concrete, cured inside the curing chamber), for which the mean shear strength of the adhesive joints (0·98 MPa) was more than double that

Table 5. Mean shear strength and mean slip modulus of each specimen, with the standard deviation and the 95% confidence interval

Specimen type	Mean shear strength: MPa	Standard deviation	95% confidence interval: MPa	Mean slip modulus: N/mm	Standard deviation	95% confidence interval: MPa
PO-NC-In-15	0·38	0·07	(0·31; 0·45)	15 298	13·55	(15 285; 15 311)
PO-NC-In-20	0·29	0·11	(0·19; 0·39)	15 650	13·10	(15 639; 15 661)
PO-NC-In-A	0·87	0·42	(0·50; 1·24)	37 247	28·13	(37 222; 37 272)
A-NC-In-15	0·73	0·19	(0·56; 0·90)	41 945	18·60	(41 929; 41 961)
A-NC-In-20	0·45	0·16	(0·31; 0·59)	29 203	16·70	(29 188; 29 218)
A-NC-In-A	2·63	0·94	(1·81; 3·45)	72 047	21·84	(72 028; 72 066)
PO-SAP-In-15	0·37	0·08	(0·30; 0·44)	18 015	19·11	(17 998; 18 032)
PO-SAP-In-20	0·40	0·12	(0·27; 0·53)	25 410	6·25	(25 403; 25 417)
PO-SAP-In-A	0·98	0·41	(0·62; 1·34)	50 554	58·17	(50 503; 50 605)
PO-NC-Out-15	0·28	0·08	(0·20; 0·36)	13 051	6·71	(13 044; 13 058)
PO-SAP-Out-15	0·39	0·07	(0·33; 0·45)	16 947	15·59	(16 933; 16 961)
PO-GGBS-In-15	0·24	0·04	(0·20; 0·28)	14 089	4·46	(14 085; 14 093)
PO-GGBS-In-20	0·22	0·06	(0·17; 0·27)	12 879	12·15	(12 868; 12 890)

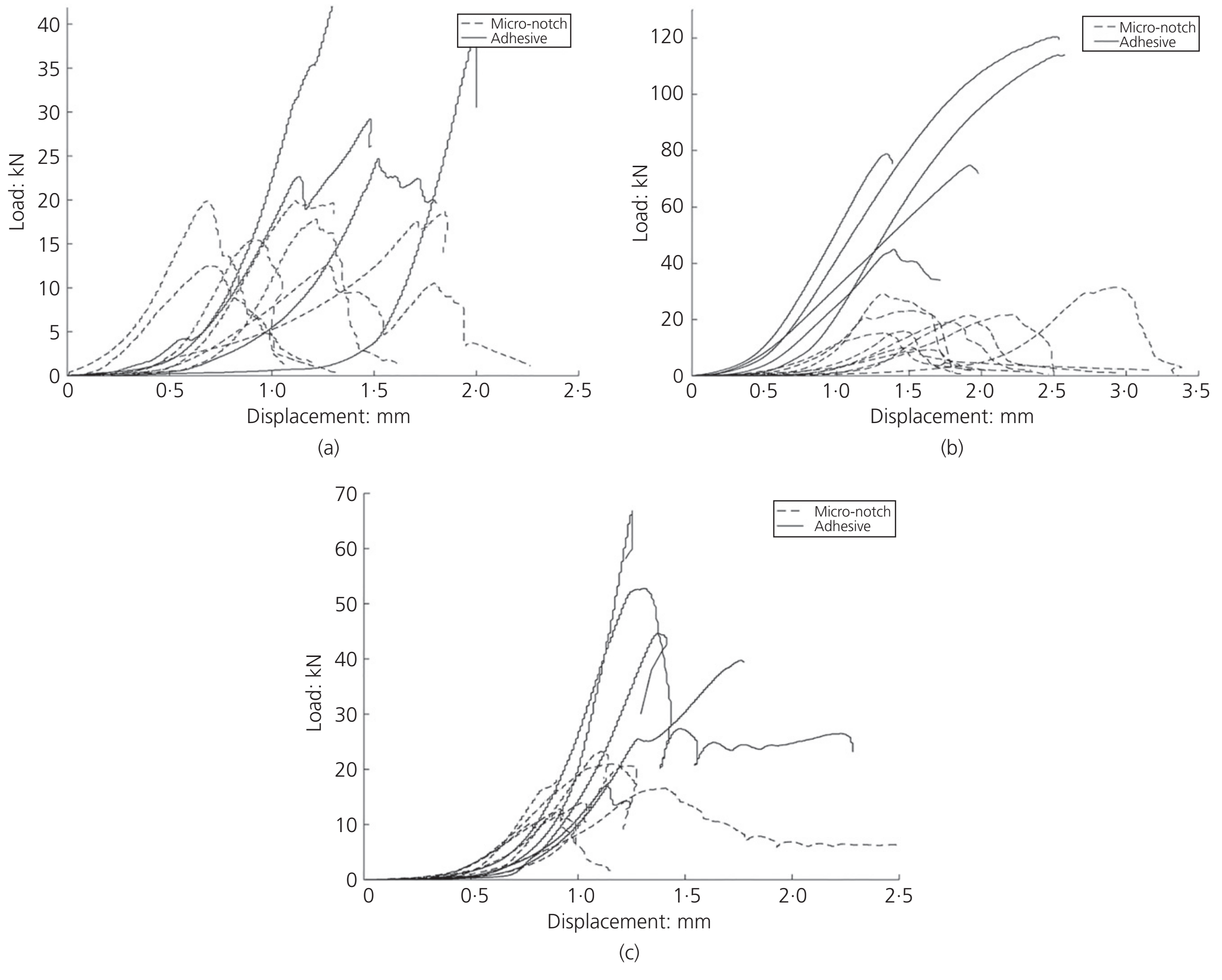


Figure 9. Experimental load–slip curves for micro notch and adhesive connections: (a) symmetrical samples, normal concrete, cured inside curing chamber; (b) asymmetrical samples, normal concrete, cured inside curing chamber; (c) symmetrical samples, SAP concrete, cured inside curing chamber

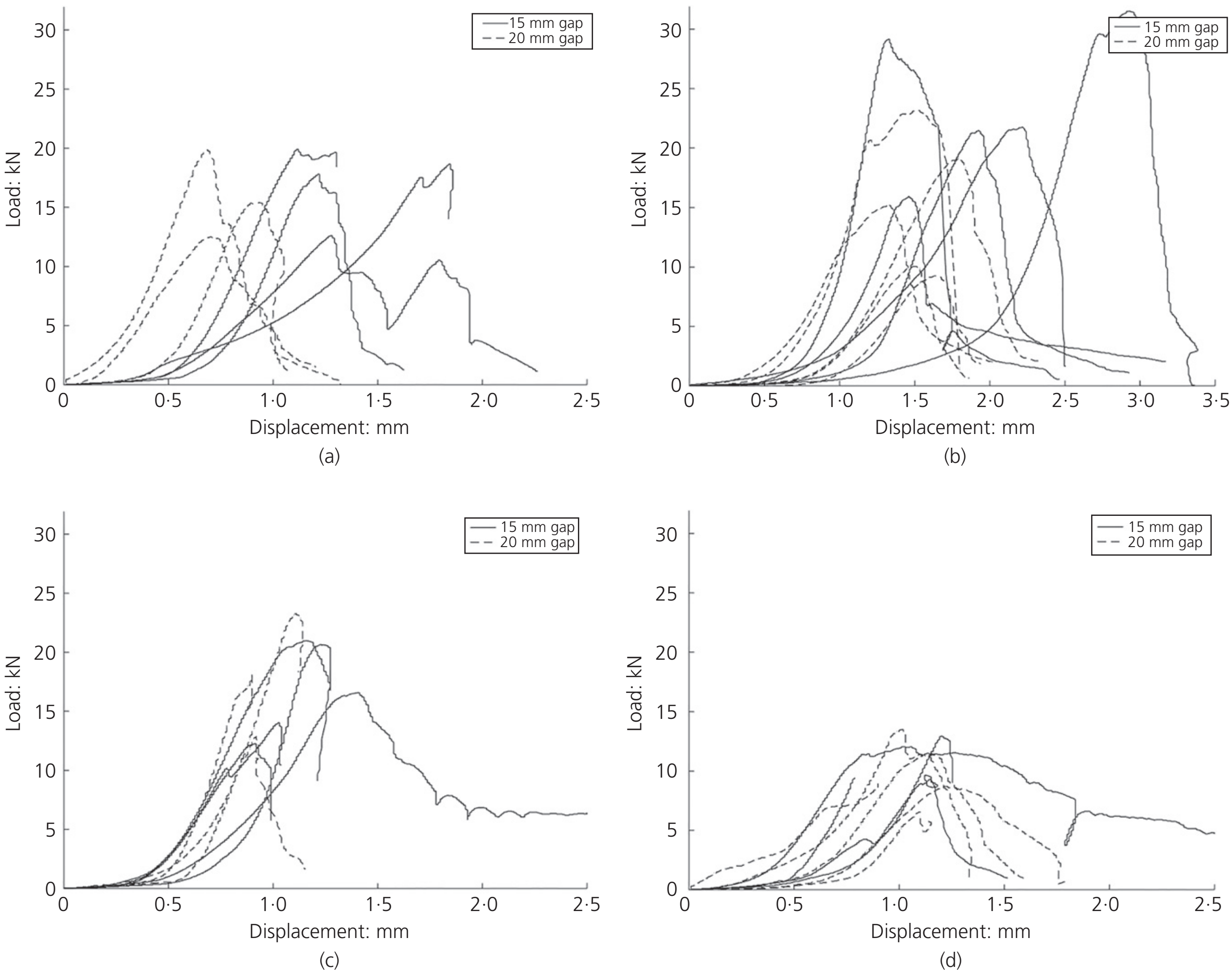


Figure 10. Influence of the gap between micro-notches (15 mm or 20 mm): (a) symmetrical samples, normal concrete, cured inside curing chamber; (b) asymmetrical samples, normal concrete, cured inside curing chamber; (c) symmetrical, SAP concrete, cured inside curing chamber; (d) symmetrical samples, GGBS concrete, cured inside curing chamber

of the micro-notch joints (0·37 MPa and 0·40 MPa) (Figure 9(c)).

5.2 Effect of the gap size between each micro-notch

Figure 10 shows the experimentally obtained load–slip curves for different micro-notched samples (15 mm gap or 20 mm gap), concrete mixtures and curing conditions. The micro-notch connectors with a 15 mm gap had, on average, a higher shear strength than those with a 20 mm gap. This could be due to the higher number of notches in the same area of the connection for the specimens with the 15 mm gap. For the first group of specimens (symmetrical samples, normal concrete, cured inside the curing chamber), the mean shear strength of the micro-notch connection with a 15 mm gap was 0·38 MPa, while its counterpart with a 20 mm gap had a mean shear strength of 0·29 MPa (Figure 10(a)). The same trend was noticeable for the second group of samples (asymmetrical, normal concrete, cured inside the curing chamber): the micro-notch connectors with a 15 mm gap had a mean shear strength of 0·73 MPa while their 20 mm counterparts had a mean shear strength of 0·45 MPa (Figure 10(b)). This trend was less noticeable for the GGBS specimens and was not applicable to the SAP concrete specimens. The concrete made with SAP had a higher compressive strength than normal concrete without SAP after 28 d. This property could interact with the beneficial effect that smaller gaps between micro-notches have on the connection's shear strength.

5.3 Effect of SAP

The load–slip curves presented in Figure 11 do not show much difference between the specimens with SAP and those without SAP (normal concrete). The mean shear strengths of the

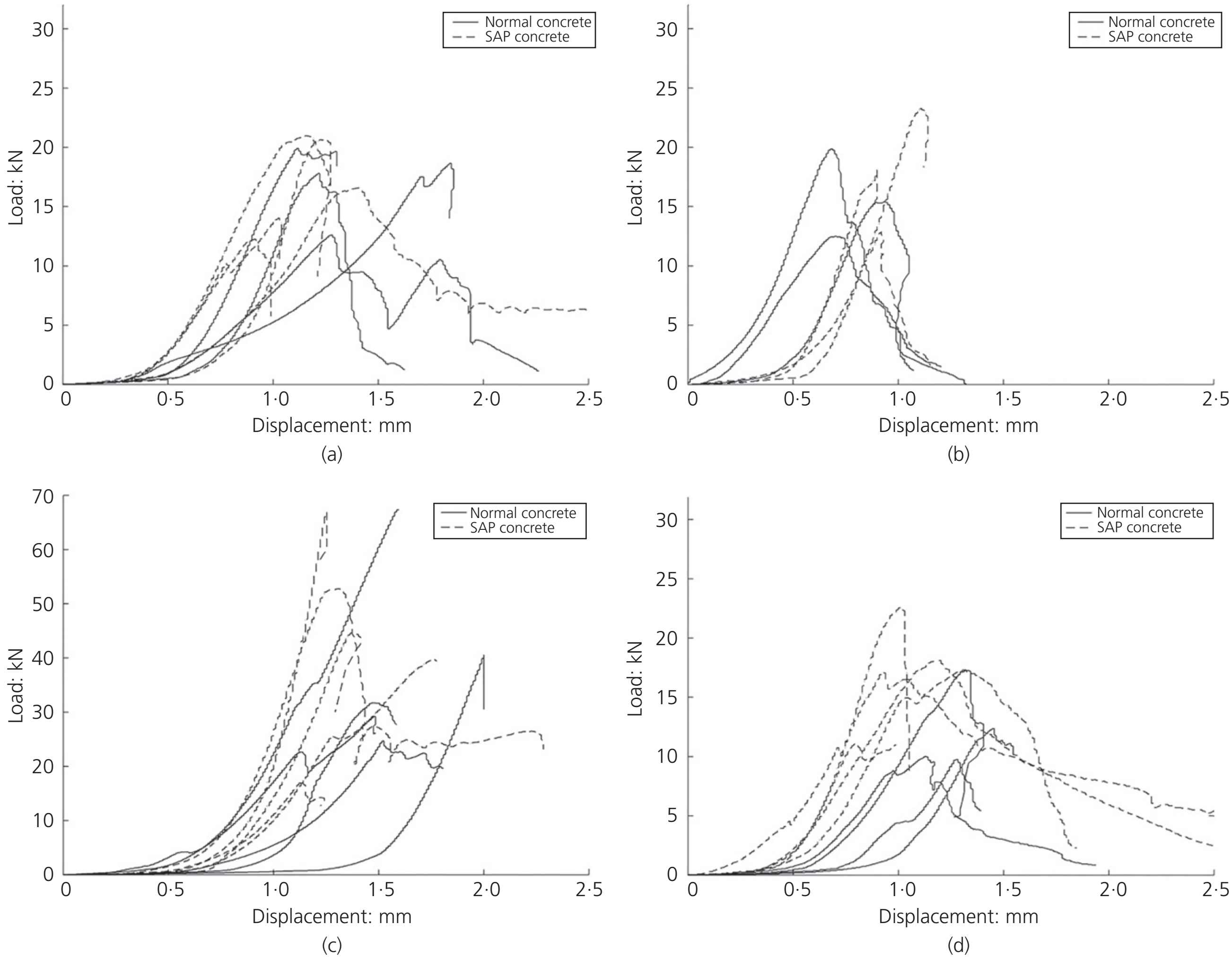


Figure 11. Load–slip curves for comparison on the presence or absence of SAP: (a) symmetrical samples, cured inside curing chamber, micro-notch connection with a 15 mm gap; (b) asymmetrical samples, cured inside curing chamber, micro-notch connection with a 20 mm gap; (c) symmetrical samples, cured inside curing chamber, adhesive connection; (d) symmetrical samples, cured outside curing chamber, micro-notch connection with a 15 mm gap

specimens with and without SAP were in the same range or slightly higher. This suggests both positive and negative impacts of SAP on the concrete's strength and finally results in similar behaviours in terms of resistance to shear stresses. The mean slip modulus of the connectors with concrete containing SAP was always superior to the mean slip modulus of their counterparts without SAP. Therefore, the presence of SAP seems to slightly enhance the stiffness of the connection. Finally, because of internal curing, the mean shear strength and the mean slip modulus for the specimens containing SAP that were cured outside the curing chamber were higher than those of the specimens cured inside the curing chamber.

5.4 Effect of GGBS

The load–slip curves of symmetrical samples made of concrete with and without GGBS are shown in Figure 12. The samples with GGBS had a lower mean shear strength than the other specimens (made of normal concrete and SAP concrete). This could result from the lower long-term resistance of concrete when half of the cement was replaced with GGBS, which has a lower reactivity than Portland cement. The compressive tests on the concrete specimens showed that the concrete made with GGBS had a lower compressive strength than the normal concrete. The slip modulus for the connectors made with GGBS concrete was lower than that of the other specimens, which translates as a lower stiffness.

5.5 Influence of the curing process

The specimens containing SAP and left to cure outside the curing chamber could rely on internal concrete curing (enabled by the properties of the SAP) instead of relying on the high humidity of the curing chamber. Figure 13 shows that, for the

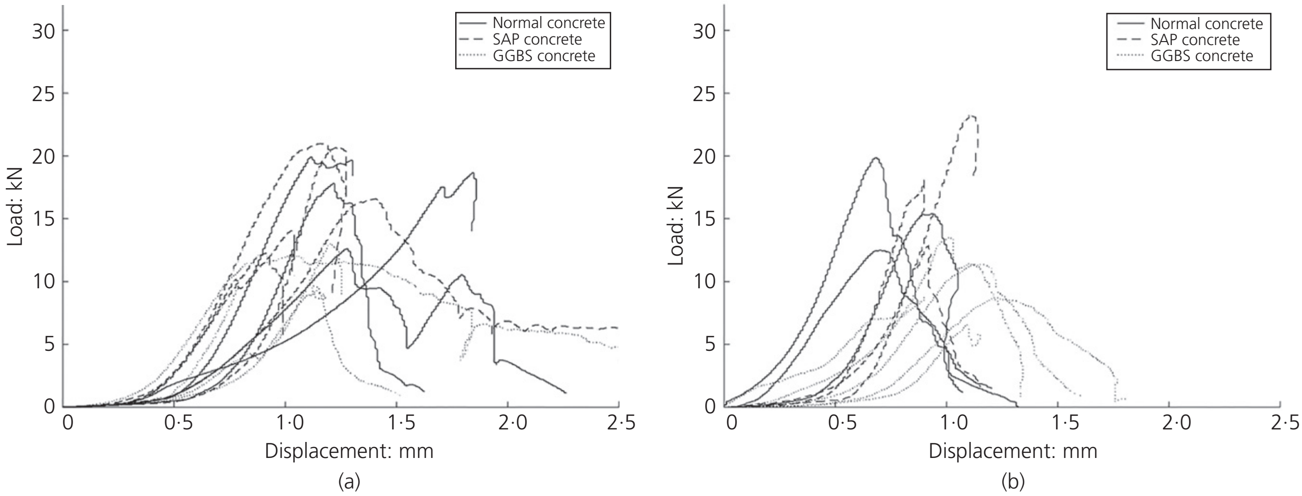


Figure 12. Load–slip curves for assessment of the effect of GGBS: (a) symmetrical samples, cured inside curing chamber, micro-notch connection with a 15 mm gap; (b) symmetrical samples, cured inside curing chamber, micro-notch connection with a 20 mm gap

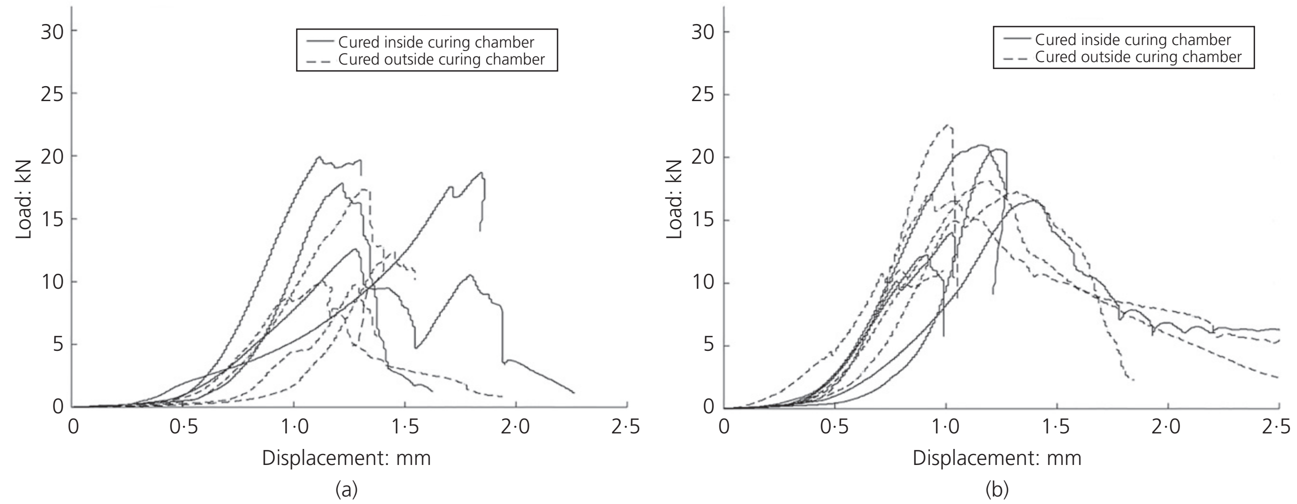


Figure 13. Load–slip curves for comparison of the curing process (inside or outside the curing chamber): (a) symmetrical samples, normal concrete, micro-notch connection with a 15 mm gap; (b) symmetrical samples, concrete with SAP, micro-notch connection with a 15 mm gap

specimens containing SAP and cured outside the curing chamber, the mean shear strength of the connections was slightly higher than that of the specimens cured inside. The shear strengths of the specimens cured outside curing chamber were found to be in the same range as those of the specimens cured inside, which shows that the specimens with SAP could rely on internal curing.

5.6 Influence of the experimental configuration

To compare the experimental configurations, Figures 14(a) and 14(b) show the load–slip curves for the symmetrical and asymmetrical tests. For the specimens with 15 mm gap micro-notches, the mean shear strength of the asymmetrical samples was 92% higher than that obtained in the symmetrical tests. For the specimens with 20 mm gap micro-notches, the shear strength of the asymmetrical samples was 55% higher.

For the adhesive connections (Figure 14(c)), the mean slip modulus of the asymmetrical samples was approximately double that of the symmetrical samples. The shear strength of the asymmetrical samples was three times higher than that of the symmetrical samples, which is abnormal. However, the failure of these specimens was different from the failure of the other specimens (see Figure 15).

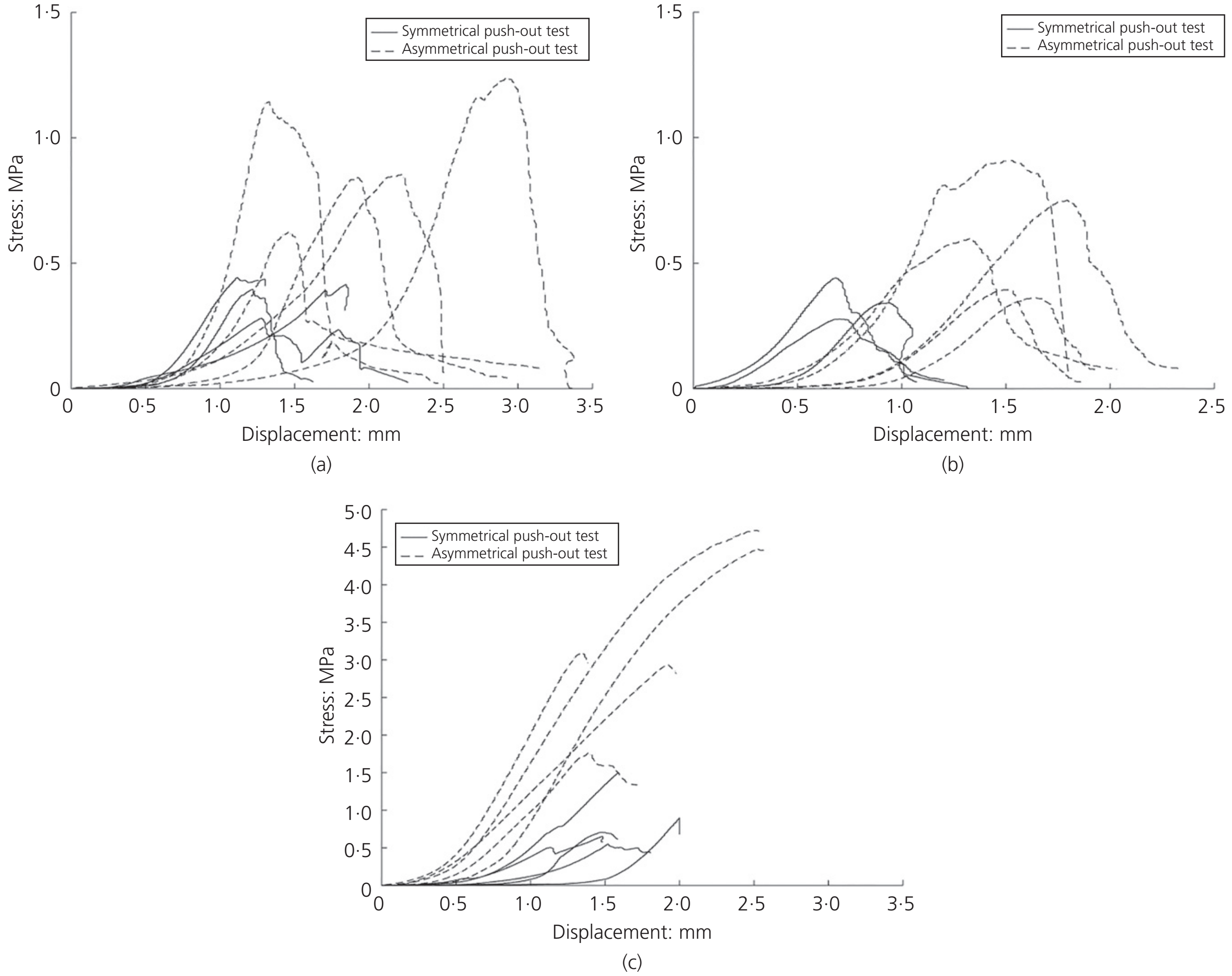


Figure 14. Stress–displacement curves for comparison of the experimental configuration (symmetrical or asymmetrical push-out test): (a) normal concrete, cured inside curing chamber, 15 mm gap micro-notch connection; (b) normal concrete, cured inside curing chamber, 20 mm gap micro-notch connection; (c) normal concrete, cured inside curing chamber, adhesive connection

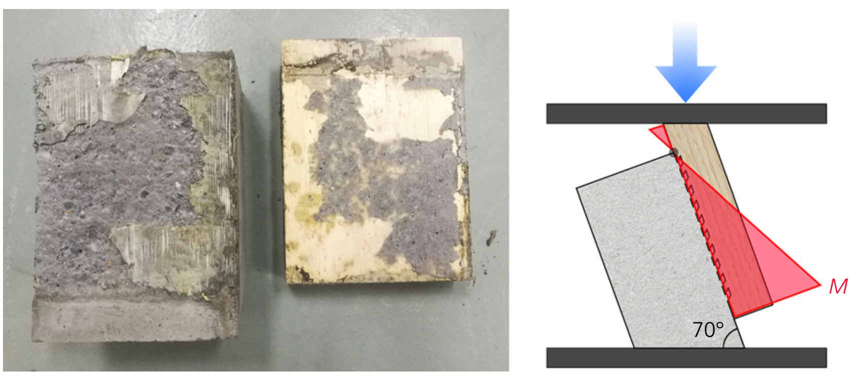


Figure 15. Failure of asymmetrical samples with adhesive joints

The measured maximum load for the adhesive joints was much higher than that of the samples (up to 121 kN) and the observed failure modes were different. For the symmetrical adhesive connections, the shear failure was entirely within the concrete layer. However, some asymmetrical shear test specimens had the adhesive layer pulled from the timber boards. The relevancy of those tests can therefore be questioned as it seems that the tensile stresses that resulted from the compressive tests prevailed on the shear stresses (see Figure 15). This shows that the specimens were more sensitive to tensile stresses than shear stresses, but also indicates that this type of test is rather imprecise as it is unknown whether the test actually focused on the shear strength of the connection and whether the tensile strength played an important part in the results.

6. Conclusions

The influences of the type and shape of the connection, the experimental configuration, the concrete composition and the curing process on the load–slip behaviour of various TCC connectors were assessed. In order to compare the different types of connections, the shear strength and the slip modulus of each specimen were measured. Additionally, two experimental configurations were investigated for the shear tests: symmetrical and asymmetrical push-out tests. Based on the investigations conducted in this study, the following conclusions can be drawn.

- Adhesive connectors have a higher shear strength and slip modulus than notched connections. Indeed, adhesive joints for TCC structures provide the highest TCC action, but are less sustainable. In addition, they are hardly workable on site.
- For micro-notched connectors, the gap between the micro-notches plays a role in the load–slip behaviour: the connectors with 15 mm gaps had a higher shear strength and slip modulus than their counterparts with 20 mm gaps.
- The use of SAP had a noticeable effect on the connections by providing additional water for internal curing of the concrete (i.e. they acted as a curing agent). The specimens made with concrete containing SAP showed higher shear strength and higher slip modulus than the other specimens.
- The addition of GGBS produced the lowest results, with the values of shear strength and slip modulus noticeably inferior to those of the other specimens. However, the replacement of 50% of the cement with GGBS did not completely undermine the shear strength and slip modulus results, and the use of GGBS adds considerable benefits to the sustainability of concrete, which cannot be neglected.
- Symmetrical push-out tests are a much more relevant setup for experimentation than asymmetrical tests. Push-out tests focus entirely on the shear strength of the connection, which is more relevant for the characterisation of TCC connectors. The results obtained from asymmetrical shear tests are hard to interpret as they also add tensile stresses that could be responsible for specimen failure.

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