

Extending 3D concrete printing to hard rock tunnel linings: adhesion of fresh cementitious materials for different surface inclinations

Yaxin Tao^{1,2}, Qiang Ren^{1,3}, Gieljan Vantghem¹, Karel Lesage¹, Kim Van Tittelboom^{1,*},
Yong Yuan⁴, Wouter De Corte^{1,2}, Geert De Schutter^{1,2}

¹*Magnel-Vandepitte Laboratory for Structural Engineering and Building Materials, Ghent University, Ghent, Belgium*

²*Belgium-China Joint Laboratory for Industrialized Construction (Ghent), Ghent University, Ghent, Belgium*

³*Key Laboratory of Advanced Civil Engineering Materials of Ministry of Education, School of Materials Science and Engineering, Tongji University, Shanghai, China*

⁴*State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*

*Corresponding author:

Kim Van Tittelboom (Kim.VanTittelboom@UGent.be)

Abstract

As an emerging automated construction technology, 3D concrete printing opens the opportunity for the construction of hard rock tunnel linings. However, very limited studies were carried out in this regard, especially the adhesion between freshly printed cementitious materials and the excavated rock wall deserves further attention. In this study, the adhesive performance of the fresh cementitious material at two representative surface inclinations, including the overhead position (inclination of 180°) and the side position (inclination of 90°), was explored by a tack test and a shear test. This was further studied by two series of 3D concrete printing tests including horizontal printing at the underside of a supported slab and vertical printing against an upright slab. Results demonstrated the adhesion at the overhead position was limited by both the shear resistance of the fresh cementitious material and the property of the material-to-substrate interface, while the adhesion at the side position was mainly constrained by the shear resistance of the fresh cementitious material. Moreover, the stress state analysis of the printed layers at the overhead position and the side position indicated that the tack test and shear test gave a good prediction about the printing capacity of the fresh cementitious material for hard rock tunnel linings.

Keywords: 3D concrete printing; hard rock tunnel lining; adhesion; excavated rock wall; surface inclination; tack test.

1 Introduction

Shotcrete has achieved significant improvements in the construction of hard rock tunnel linings with the advantages of versatility and cost-saving [1, 2]. However, this technology also introduces some adverse aspects such as a high amount of rebound during the spraying process [3]. Rebound is defined as a part of the sprayed material that ricochets and does not stick to the excavated rock wall [4]. Several factors have been proposed to influence the amount of rebound such as the surface hardness, the presence of steel mesh reinforcement, and the inclination of the surface. Specifically, the amount of rebound would reduce with less ricochet as the hardness of the projected surface decreased. Installing steel mesh reinforcement can also be used to diminish the rebound. It was also reported that the amount of rebound would vary between 2-5% on floors, 5-10% on vertical sidewalls, and up to 10-15% on overhead surfaces [5, 6]. Apart from the issues mentioned above, the key point is adopting proper operations such as the nozzle angle to the substrate, the nozzle distance to the substrate, and the thickness of one sprayed layer, which is strongly determined by the technical proficiency of the operator [5]. However, the shotcrete quality and the amount of rebound is hard to control and is highly dependent on the skills of the operator.

Based on the shotcrete technology, a shotcrete-based 3D concrete printing technique has been developed [7-9], which belongs to the category of automated robotic additive manufacturing technologies. By using the shotcrete-based 3D concrete printing technique for the construction of hard rock tunnel linings, the degree of automation and precision can be optimized. Unfortunately, the rebound cannot be avoided due to the presence of a high-speed spraying process. Compared to the shotcrete or shotcrete-based 3D concrete printing with unavoidable rebound, extrusion-based 3D concrete printing has the potential to clear off the waste of rebound using a relatively low extrusion speed [10-12]. However, very limited studies focused on this topic, especially on the adhesion of the freshly printed cementitious materials onto the rock. The influence of surface inclinations, which is an important aspect for controlling the amount of rebound in the context of shotcrete [5], on the adhesive performance of freshly printed materials was not studied previously.

In the actual situation, the fresh cementitious material should be printed against the whole excavated surface. However, only two representative conditions are considered in this study including the inclination angles of 180° and 90° , which represent the overhead position (the crown of the tunnel wall) and the side position, respectively, as schematically illustrated in Fig. 1. First, the adhesion of the fresh cementitious material at these two surface inclinations was measured by a tack test and a shear test. Further, two series of

large-scale 3D concrete printing tests were performed with a horizontally supported slab and a vertical slab. Finally, the stress state of these two cases was analyzed.

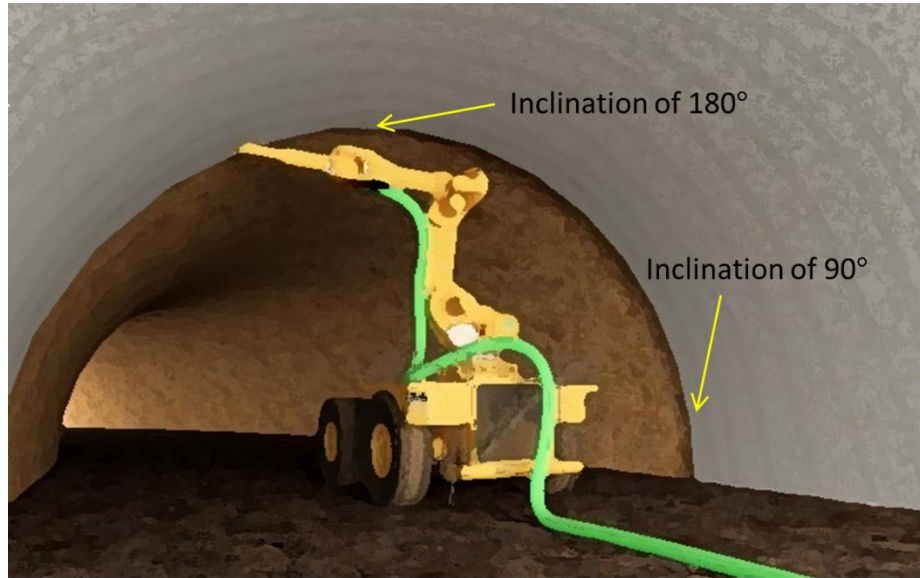


Fig. 1 Schematic view of 3D concrete printing for hard rock tunnel linings including the inclination from 90° (side position) to 180° (overhead position).

2 Experimental program

2.1 Materials and mixing procedure

Mixture compositions consisted of silica sand provided by Vandeveld NV (specific gravity 2650 kg/m³, maximum particle size 2 mm, fineness modulus 2.05), CEM I 52.5 N Portland cement provided by Holcim (specific gravity 3160 kg/m³, Blaine specific area 408 m²/kg), superplasticizer provided by BASF (liquid polycarboxylate ether, MasterGlenium 51, concentration 35%), cellulose ether provided by SE Tylose (MB 60000 P2, main component hydroxyethyl methylcellulose, viscosity of 1.9% solution 30,000 mPa·s at 20 °C), and water. To take the shear resistance of the fresh cementitious material into consideration in this study, three mixtures were prepared including M1, M2, and M3 with the same sand to binder ratio of 1 and the same water to binder ratio of 0.35. The dosages of the superplasticizer were 0.1%, 0.3%, and 0.5% by the mass of binder for mixture M1, M2, and M3, respectively. Different from other 3D concrete printings (from bottom up), the tunnel linings are printed against the rock wall for different surface inclinations. Besides the basic requirements of 3D printable concrete, e.g. pumpability, extrudability, and buildability, the mixture used for tunnel linings should meet the requirement of adhering to the excavated rock walls. Thus, hydroxyethyl methylcellulose

was added with a dosage of 0.2% by the mass of cement for all mixtures. The mix proportions of the three mixtures used in this study are shown in [Table 1](#).

Table 1 Mixture design of the material (kg/m³).

Mixture	Sand	Cement	Water	Hydroxyethyl methylcellulose	Superplasticizer
M1	958.0	958.0	335.3	1.916	0.958
M2	958.0	958.0	335.3	1.916	2.874
M3	958.0	958.0	335.3	1.916	4.790

Small mixture batches (around 1.5 liters) were prepared in a planetary mixer with the following mixing protocol: (1) manually mixing superplasticizer with water for 10 s; (2) adding water (and superplasticizer) to cement and rotating the paddle at 140 rpm for 30 s; (3) adding silica sand and rotating the paddle at 140 rpm for 30 s; (4) rotating the paddle at 285 rpm for 30 s; (5) scraping and resting for 90 s; (6) rotating the paddle at 285 rpm for 60 s; (7) adding viscosity modifying admixture and mixing at 285 rpm for 30 s. Small mixture batches were used for the stress growth test, the tack test, and the shear test, which will be introduced in Section 2.3. In addition, big mixture batches (around 20 liters) were prepared in a pan mixer for 3D concrete printing tests with the following mixing protocol: (1) manually mixing superplasticizer with water for 10 s; (2) mixing silica sand and cement for 30 s; (3) adding water (and superplasticizer) to the dry materials (silica sand and cement) and mixing for 180 s; (4) adding viscosity modifying admixture and mixing for 60 s. The total mixing period for both batches was 280 s.

2.2 Substrate preparation

For an actual tunnel wall, the surface roughness might be the most important characteristic considering the adhesion performance [\[13\]](#). The surface roughness of the excavated rock wall is influenced by several factors such as the excavation methods and the rock properties. For example, by using the tunnel boring machine (TBM) method, the excavated surface is smooth. However, the excavated tunnel wall would have an undulating surface by using the drill-and-blast method. In addition, the blasted rock wall is more smooth when excavating a homogeneous rock mass, rather than a jointed area [\[14\]](#). In this study, a wide range of roughness levels is studied by using several typical removal technologies including polishing, sandblasting, hammering, and water-jetting [\[15\]](#). Two concrete mixtures of micro-concrete and crushed stone concrete were used to make the substrates. The concrete substrate mix design and characteristics can be found in [\[15\]](#). In this study,

only the fresh properties of 3D printable concrete were investigated and all experiments were performed in a very short period (within several minutes). Based on this, it is expected that the physical effect plays a key role, while the chemical interaction between the fresh overlay and the hardened substrate can be ignored. Therefore, calcium-rich concrete substrates were used to replace silica-rich rock walls without further considering the type of rock mineral.

To determine the compressive strength of the substrate, 3 cubes (150×150×150 mm) for each mixture were tested according to NEN-EN 12390-3 (2009) [16]. The values were 35.3 MPa and 37.0 MPa at the age of 28 days for the micro-concrete and crushed stone concrete respectively. Two types of micro concrete slabs treated by polishing (Flex, LE 12-3 100 Wet, polishing for 24 minutes, R1-A and R1-B) and sandblasting (pressure 0.7 MPa, R2-A and R2-B) were prepared. Another two types of crushed stone concrete slabs treated by hammering (Air Hammer model 29062, 3000 strokes per min, R3-A and R3-B) and water jetting (high pressure of 130 MPa, R4-A and R4-B) were prepared. Two cylindrical samples (diameter 50 mm) were drilled from each type of slab and in total eight cylindrical samples were prepared, as shown in Fig. 2. The treated surface of each concrete cylindrical sample was scanned by using automated laser measurements (ALM) with a high precision laser sensor (ILD 1800-50, resolution 5 μm) [15, 17]. The treated surface profile of each concrete cylindrical sample was scanned four times along different diametric scanning paths and the profile height along with the evaluation position was recorded. The roughness levels of the lower surfaces were characterized by the root mean square deviation R_q (mm), which was in accordance with BS 1134 (2010) [18], as follows:

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n Z_i^2} \quad (1)$$

where n is the number of measurements and Z_i is the amplitude of each test (mm).

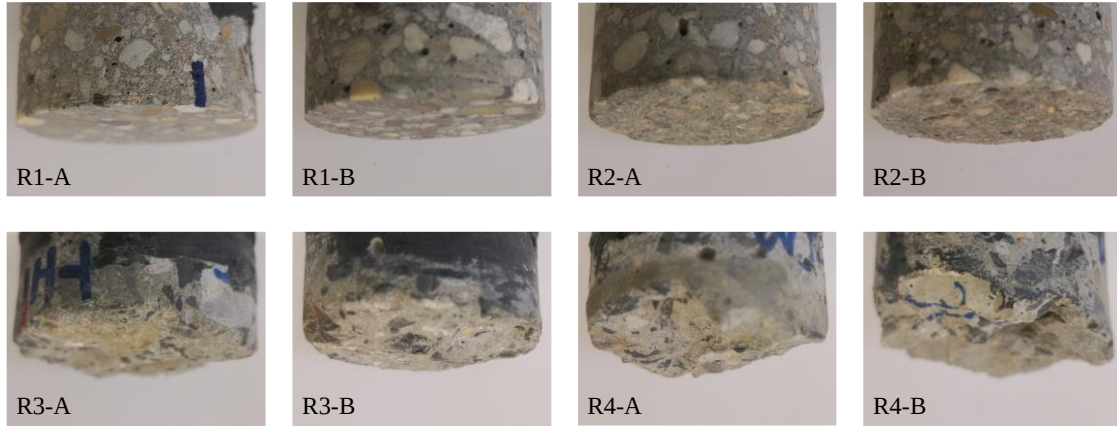


Fig. 2 Concrete cylindrical samples with different roughness levels: R1-A and R1-B: polished surface; R2-A and R2-B: sandblasted surface; R3-A and R3-B: hammered surface; R4-A and R4-B: water-jetted surface.

The R_q values of the treated surfaces of the eight concrete cylindrical samples are shown in Fig. 3. It was shown that the R_q values of the cylindrical samples varied from an average value of almost 0 (polished samples) to around 2.5 mm (water-jetted samples).

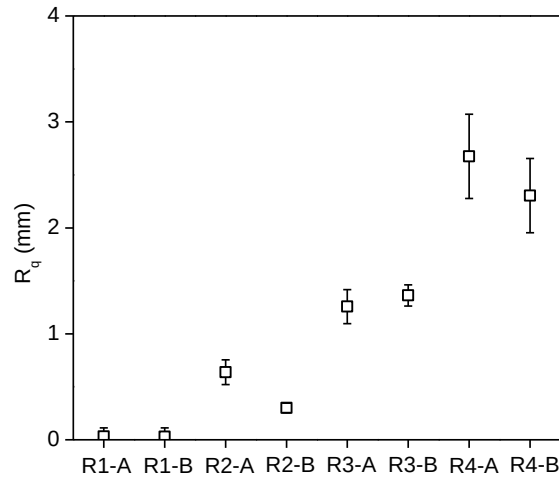


Fig. 3 Root mean square deviation (R_q) of the lower surface of the cylindrical samples (error bars represent the standard error, $n=4$).

The sandblasted substrate was chosen for 3D concrete printing tests. In this study, six sandblasted slabs ($1000 \times 120 \times 50 \text{ mm}^3$) were prepared to replace the excavated rock wall in 3D concrete printing tests.

Before performing tests (i.e. the tack test, shear test, and 3D concrete printing test), concrete substrates including cylindrical samples and strokes were submerged in water for 24 h and swept by soft tissue to obtain a saturated-surface-dry surface moisture content. After each measurement, the slab was cleaned by a water gun and followed the same moistening procedure for controlling the moisture content for each series.

2.3 Testing procedures

2.3.1 Stress growth test

A stress-controlled rotary rheometer (Anton Paar MCR 52) was employed to perform the stress growth test. The building material cell and the 6-blade vane rotor were used. 24 vertical ribs (1 mm width) are uniformly placed at the inner surface of the building material cell to prevent wall slippage. The fresh cementitious material was placed inside the cell to make sure that the blades were covered. After that, the blades were sheared at a constant rotational speed of 0.1 rpm with a total period of 200 s and rotational torque values were recorded. The test was repeated two times for each series. The setup for the stress growth test and its dimensions are shown in [Fig. 4](#).

The maximum shear stress τ_y (Pa) was calculated as follows:

$$\tau_y = \frac{T_{max}}{2\pi R^2 h} \quad (2)$$

where T_{max} is the maximum torque (N·m), R is the radius of the blade geometry (0.011 m), h is the height of the blades (0.016 m).

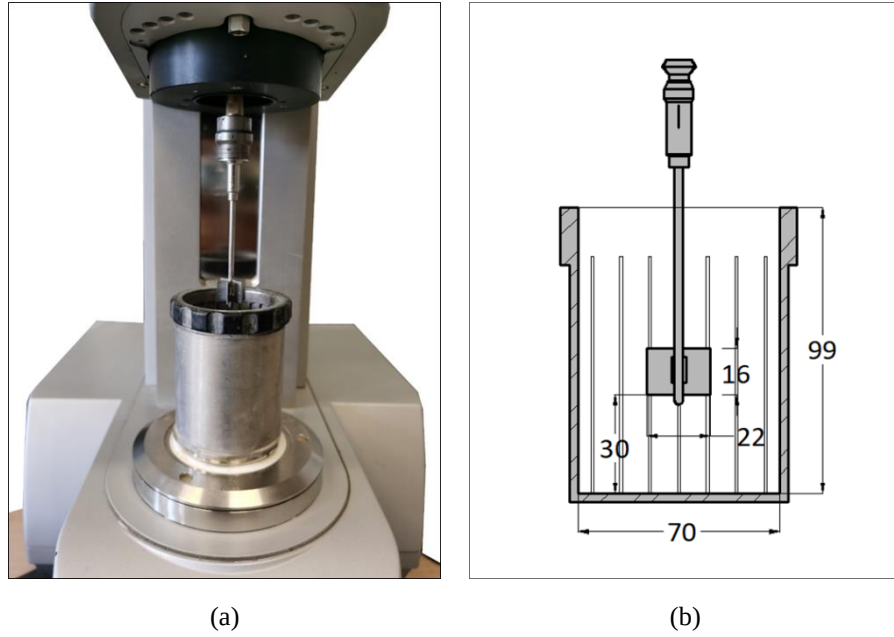


Fig. 4 (a) Setup for the stress growth test, and (b) dimensions (mm).

2.3.2 Tack test

A rheometer (Anton Paar MCR 102) with a parallel-plate geometry (diameter 50 mm) was used for the tack test. Then, the concrete cylindrical samples described in Section 2.2 were glued to the top plate. Circular sandpaper with the same diameter as the plates (root mean square deviation R_q 0.18 mm) was glued onto the bottom plate of the rheometer. The tack test was performed using the following steps: (1) placing a plastic circular mould (inner diameter 50 mm, height 20 mm) on the bottom plate and fixing by hand, (2) putting the fresh cementitious material in the plastic circular mould and flattening the sample surface, (3) Removing the circular plastic mould, (4) moving the concrete cylindrical sample downwards until the gap between the lower surface of the concrete sample and the bottom plate reached 10 mm, which is equal to the thickness of one printed layer, (5) pulling off the concrete cylindrical sample at a constant speed of 50 $\mu\text{m/s}$ for a maximum period of 500 s and recording the normal force and displacement. Then, a new moulding procedure was performed and the experiment was repeated twice for each mixture (M1-M3) and each roughness level (R1-R4). The setup for the tack test and its dimensions are shown in Fig. 5.

The tensile stress σ_t (Pa) and strain ε_t (-) were derived from the recorded normal force and displacement, as follows:

$$\sigma_t = \frac{4F}{\pi d^2} \quad (3)$$

$$\varepsilon_t = \frac{\Delta L}{L} \quad (4)$$

where F is the normal force (N), d is the diameter of the concrete cylindrical sample (m), ΔL is the displacement of the concrete cylindrical sample (m), and L is the initial distance between the lower surface of the concrete sample and the bottom plate (m).

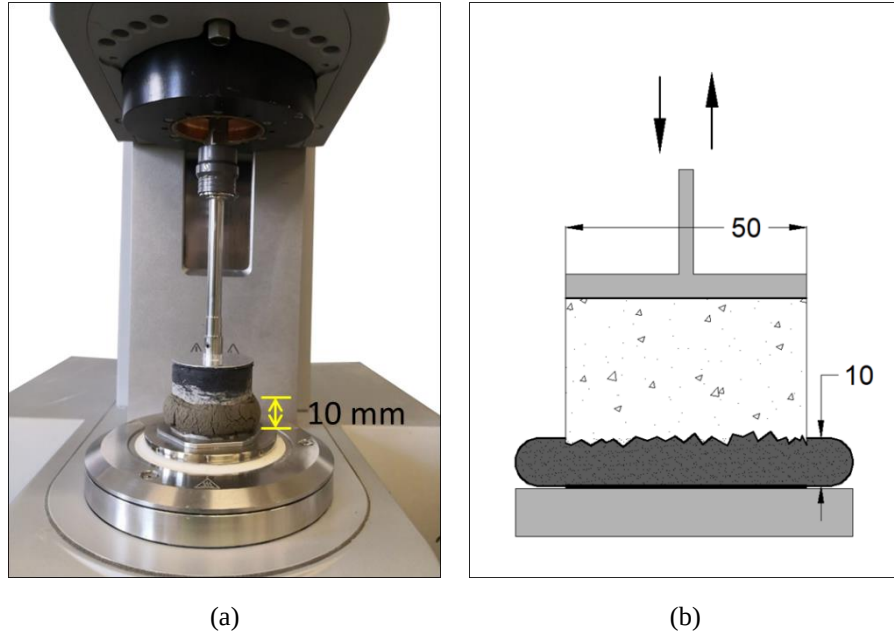


Fig. 5 (a) Setup for the tack test and a squeezed sample, and (b) dimensions (mm).

2.3.3 Shear test

The shear test was performed with the rheometer used for the stress growth test (Anton Paar MCR 52). The shear test was performed using the following steps: (1) fixing a plastic circular container (inner diameter 100 mm, height 25 mm) on the bottom module of the rheometer, (2) putting the fresh cementitious material in the plastic circular container and flattening the sample surface, (3) moving down the concrete cylindrical sample until the lower surface was submerged inside the fresh cementitious material to a depth of 10 mm, (4) rotating the shaft with a constant rotational speed of 0.1 rpm for a total time period of 100 s and recording the torque values. Then, a new moulding procedure was performed and the experiment was repeated twice for each mixture (M1-M3) and each roughness level (R1-R4). The setup for the shear test and its dimensions are shown in Fig. 6.

Under the assumption that the fresh cementitious material reaches the yield point in the whole circular plane, the shear stress τ_s (Pa) is given as:

$$\tau_s = \frac{12T}{\pi d^3} \quad (5)$$

where T is the torque value (N·m) and d is the diameter of the concrete cylindrical sample (m).

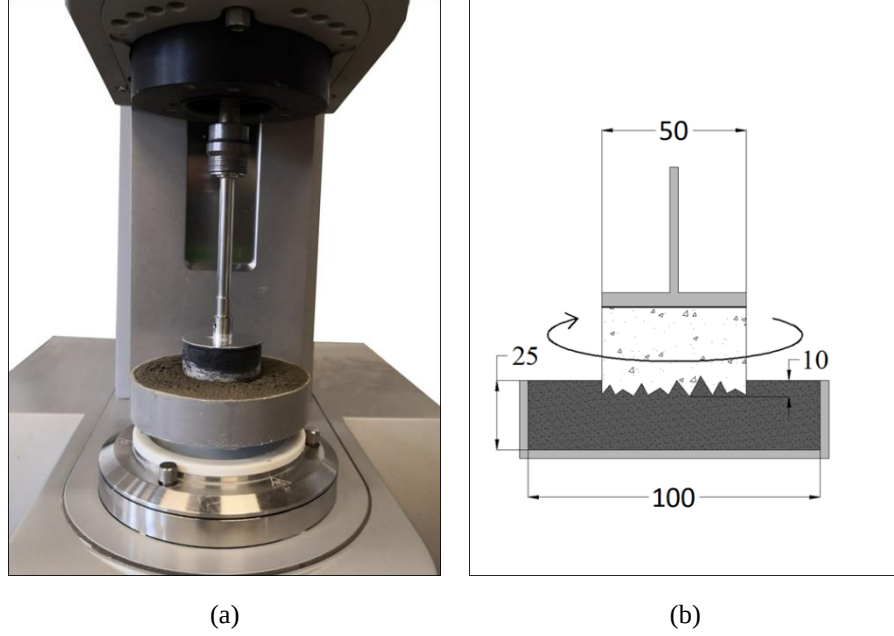


Fig. 6 (a) Setup for the shear test and (b) dimensions (mm).

2.3.4 3D concrete printing test

Two groups of 3D concrete printing tests were performed at two representative surface inclinations including the inclination of 180° (overhead position) and the inclination of 90° (side position), as shown in Fig. 7. The 3D printing system was composed of a 6-axis robotic arm (ABB IBR 6650), a worm pump (MMB STROBOT 407), a 3D printed plastic nozzle (printer: Ultimaker 2+, material: standard PLA), and a pumping pipe (length 3 m, diameter 25.4 mm). A schematic view and dimensions of the 3D printed plastic nozzle are shown in Fig. 8. The width of extruded layers was 60 mm and the thickness was 10 mm for both series. The layers were printed with a continuous path (length 600 mm). In the series of printing at the overhead position, the slab was supported horizontally at two lateral sides with the sandblasted surface facing downwards. The layers were printed against the lower surface of the sandblasted slab, while in another series, the sandblasted slab was

placed vertically, as well as the printed layers. A digital camera was used to record the whole printing process. For each mixture (M1-M3), the test was repeated three times.

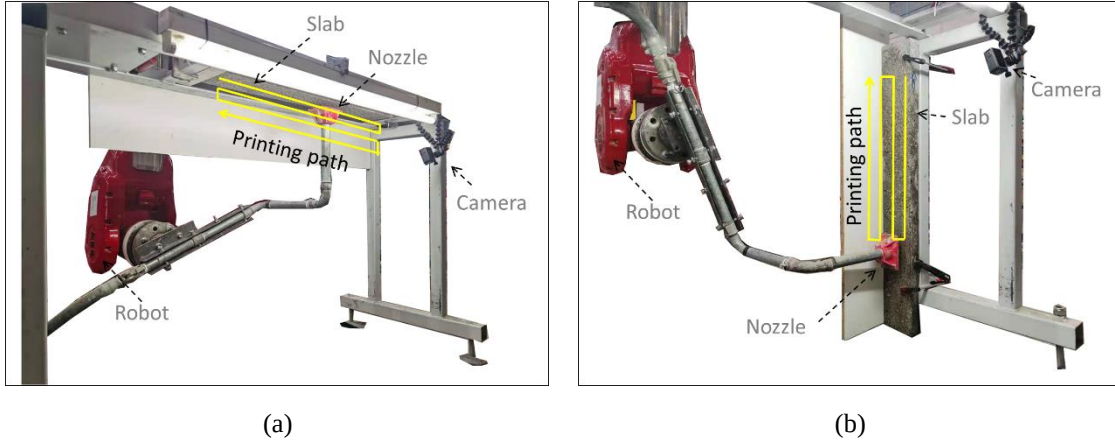


Fig. 7 3D concrete printing setup: (a) printing at the overhead position and (b) printing at the side position.

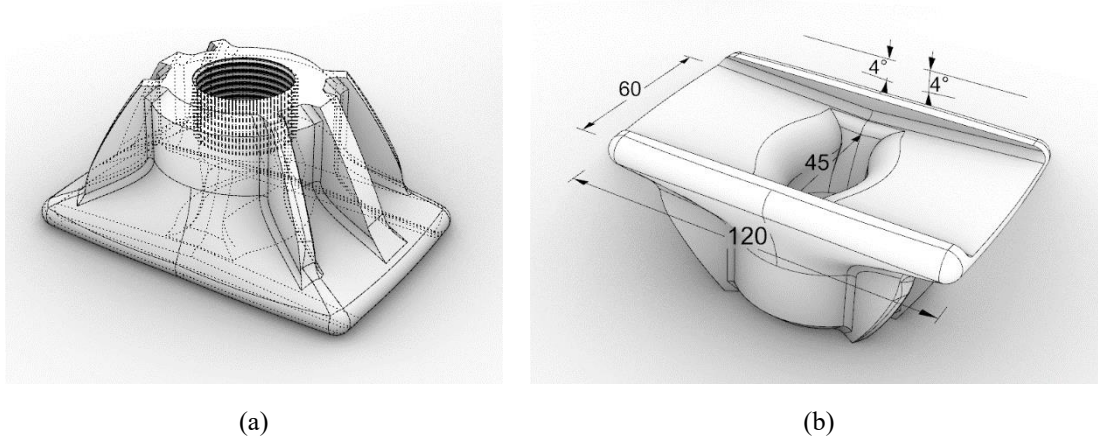


Fig. 8 Schematic view and dimensions (mm) of the 3D printed plastic nozzle.

3 Results and discussion

3.1 Adhesion in the tension state

Tensile stress versus strain curves obtained from the tack test are shown in Fig. 9. At the early beginning of the test, the fresh cementitious material deformed elastically and the tensile stress presented a semi-linear increase along with the increase of the displacement. After the tensile strain of the fresh cementitious material exceeded a critical value, the tensile stress decreased gradually to zero, indicating that the fresh cementitious material underwent a failure process [19, 20].

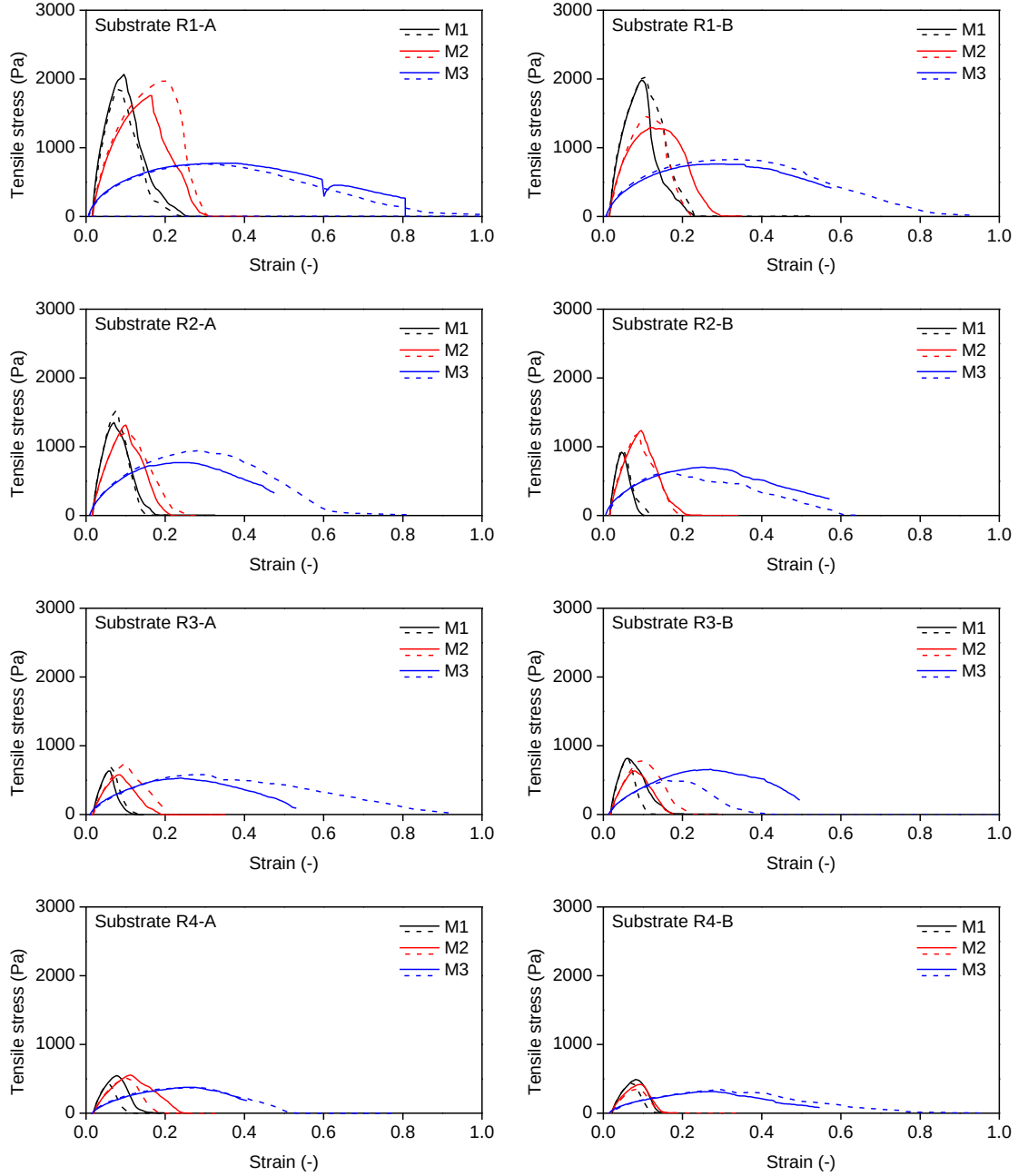


Fig. 9 Tensile stress versus strain curves obtained in the tack test (solid and dashed lines indicate two repetitions of each series).

The peak values of the tensile stress were used to quantify the adhesive strength of the fresh cementitious material [19], as shown in Fig. 10. It was found that the peak tensile stress reduced as the substrate roughness increased. Specifically, the average value of the peak tensile stress of mixture M1 decreased from 1960.79 Pa to 468.55 Pa as the root mean

square deviation value (R_q) increased from 0.03 to 2.68, while the average value of the tensile stress of mixture M3 decreased from 769.04 Pa to 331.04 Pa as the R_q value increased. Additionally, in the case of substrate R1-A, a difference of 60.8% was observed when comparing the peak tensile stress of mixture M1 and mixture M3 (1960.79 Pa and 769.04 Pa), while such a difference between the peak tensile stress of mixture M1 and mixture M3 was only 29.4% in the case of substrate R4-B. A two-way ANOVA test was conducted to examine the effect of the mixture type and the roughness level on the peak tensile stress obtained in the tack test. A p-value less than 0.05 ($p < 0.05$) was considered statistically significant. According to the results, there was a statistically significant interaction between the effects of the mixture type and the roughness level on the peak tensile stress ($p = 0.000$). For the order of roughness levels, the groups were pair-wise compared with a Bonferroni test. A significant difference was observed when we pair-wise compared all three mixture types.

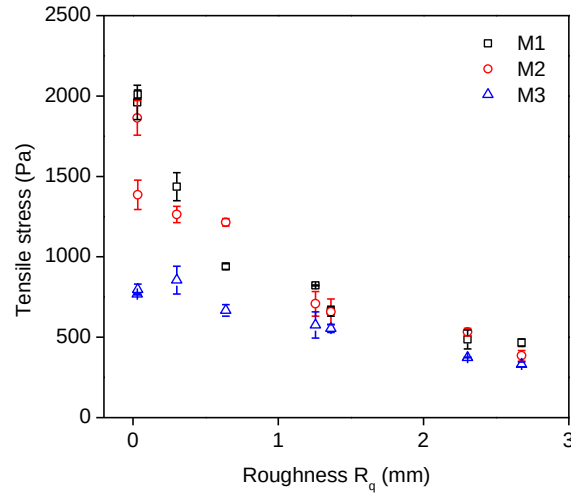


Fig. 10 Effect of roughness levels and mixture types on peak tensile stress (error bars represent the standard error, $n=2$).

Another interesting point relates to the critical strain corresponding to the peak tensile stress and the total strain at the moment of failure. As can be observed in Fig. 10, both the critical strain and the total strain increased when more superplasticizer was added to the matrix (from M1 to M3). For example, in the case of using the substrate R2-A (sandblasted), the average values of critical strain were 0.07, 0.10, and 0.25 for the mixtures M1, M2, and M3, respectively. In addition, as compared to mixtures M1 and M2, mixture M3 obtained the highest energy absorption, which was calculated from the area formed by the tensile stress curve and the horizontal axis. The difference in the strain values and the energy absorption can be further correlated to the failure patterns during the tack test.

Taking the concrete cylindrical sample R2-A as an example, the failure patterns of the three mixtures M1, M2, and M3 are shown in Fig. 11. Distinguished from the adhesion of the cementitious materials in hardened state that is mainly attributed to mechanical interlocking [21-23], the adhesion of the cementitious materials in fresh state is related to some other aspects. It was pointed out by Mohamed et al. [24] that the effort required to lift the top plate was determined by the inward flow of the fresh sample. At the early stage of the pull-off process, a short movement of the top plate would induce a significant inward flow at the air-to-sample interface. The inward flow of the fresh sample is determined by both viscous dissipation (dynamic performance) and cohesive strength (static performance). In this study, a relatively low pulling velocity ($v = 50 \mu\text{m/s}$) was used and the whole testing process can be treated as a quasi-static process. Therefore, the viscous dissipation, which is related to the dynamic performance of the material, was not considered [20]. Further, such an inward flow is constrained by the friction provided by the top and bottom plates. As a result, the peak tensile stress depended on the shear resistance of the fresh sample and the sample-to-plate interface. It was assumed that the contact area at the interface was limited when using a more solid-like material such as mixture M1. As such, less friction confining the inward flow of the fresh cementitious material was provided at the interface and the adhesion was compromised accordingly. This can also be reflected by the lower strain values and energy absorption for the solid-like mixtures. Reversely, for mixture M3 with a more liquid-like behavior, more contact between the lower surface of the concrete cylindrical sample and the fresh cementitious material was expected (see Fig. 11 (c)). As a result, the liquid-like mixture allowed larger strain values. However, the fracture occurred in the bulk of the fresh cementitious material and the lower shear resistance of the mixture limited the adhesive strength.

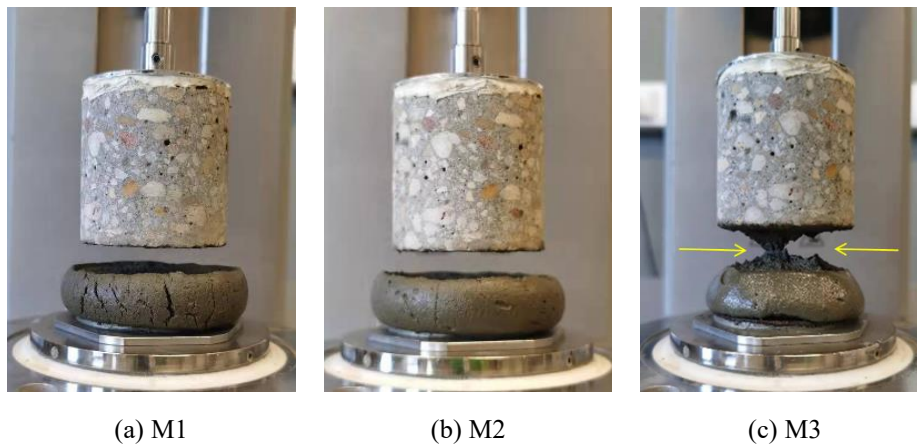
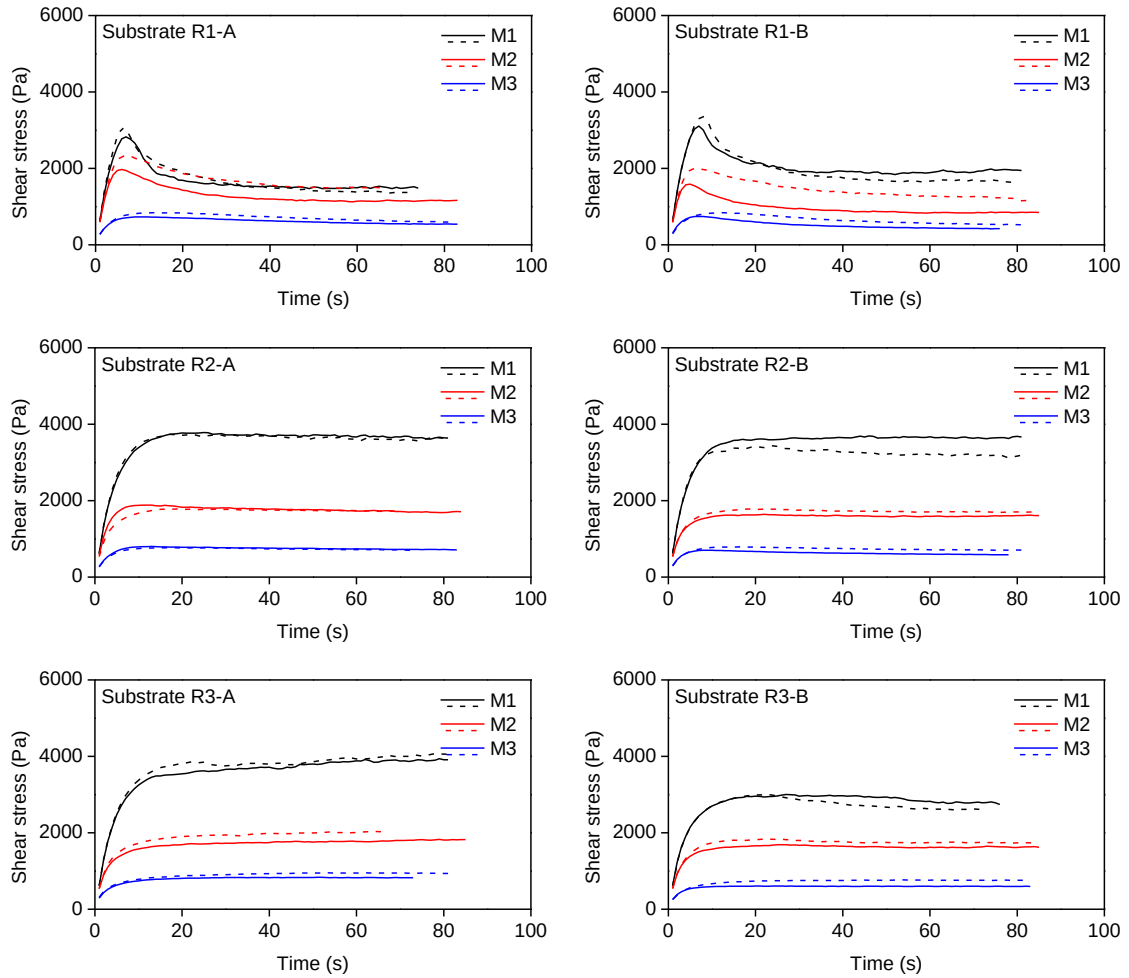


Fig. 11 Failure patterns of the mixtures M1, M2, and M3 when using the concrete cylindrical sample R2-A, yellow arrows indicate the inward flow of fresh cementitious material.

3.2 Adhesion in the shear state

The shear stresses were recorded in the shear test, as shown in Fig. 12. The shear stress evolution curves obtained in the shear test followed two different patterns. For the cylindrical samples with a low roughness level such as R1-A and R1-B, an obvious peak was observed, while for the rest of the cylindrical samples with higher roughness levels, it was observed that a plateau followed an increasing stage.



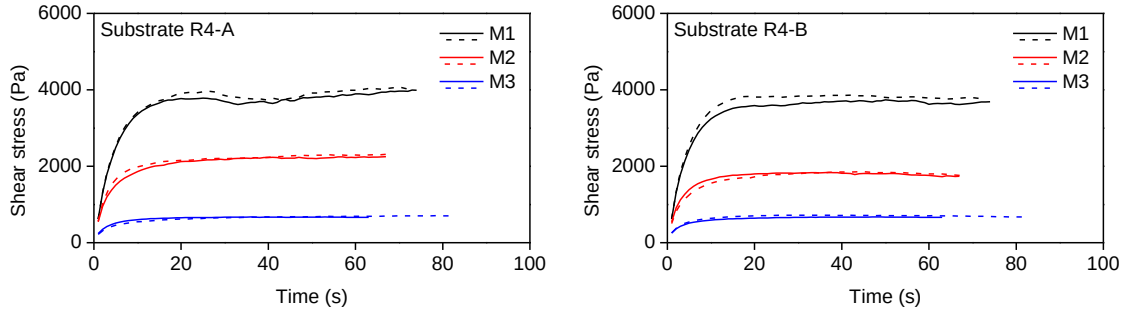


Fig. 12 The shear stress evolution along with time obtained in the shear test (solid and dashed lines indicate two repetitions of each series).

Maximum values of shear stress derived from the shear stress evolution curves are shown in Fig. 13. Generally, mixture M1 presented the highest shear stress while mixture M3 had the lowest shear stress value. For example, the maximum shear stress of mixture M1 reached an average value of 2944.99 Pa while the maximum shear stress of mixture M3 was merely 785.93 Pa in the context of using substrate R1-A. In addition, a two-way ANOVA test was conducted to examine the effect of the mixture type and the roughness level on the maximum shear stress obtained in the shear test. The statistical analysis followed the same procedure introduced in Section 3.1. Results indicated that no interaction existed between the two factors in the discrimination performance analysis, but respective differences were noted in the two dependent variables. For the mixture type, significant differences were observed when we compared different mixture types while no significant difference appeared between different substrates.

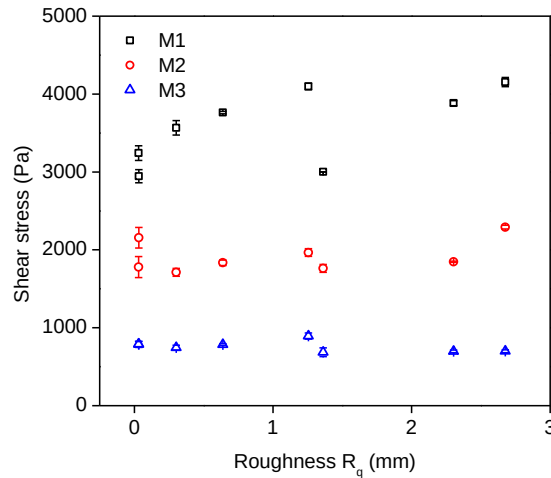


Fig. 13 Maximum shear stress measured for different concrete substrates (error bars represent the standard error, $n=2$).

Further, the maximum shear stress (i.e. yield stress) was measured in the stress growth test. The average values were 3460.59, 2297.14, and 545.05 Pa for mixture M1, M2, and M3, respectively. Since no significant difference existed when comparing different substrates in the shear test, the maximum shear stress measured with the sandblasted substrate R2-A was chosen. The average values were 3761.97, 1834.17, and 783.87 Pa for mixture M1, M2, and M3, respectively. Afterward, the maximum shear stress measured in the shear test (τ_s) and the maximum shear stress measured in the stress growth test (τ_y) were linearly fit, as shown in Fig. 14. A good linear relationship ($R^2 = 0.8885$) was obtained. Such a result proved that the shear resistance of the bulk of the fresh cementitious material played a decisive role in the adhesion in the shear state.

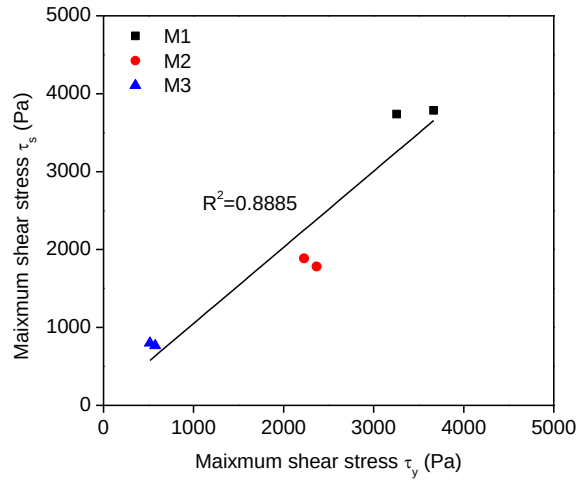


Fig. 14 Maximum shear stress measured in the shear test and stress growth test (error bars represent the standard error, $n=2$).

3.3 3D printing test results

The results of the 3D concrete printing tests at the overhead position are shown in Fig. 15. For each mixture, one of the three representative repetitions is shown including the moment when the maximum number layers were printed (left), when the failure occurred (middle), and the moment after failure (right). As presented in Fig. 15 (a), the maximum number of printed layers of mixture M1 amounted to 7, which was followed by a debonding at the interface between the lower surface of the slab and the fresh cementitious material. For mixture M2, 6 layers were printed before failure occurred, which was slightly less than that of mixture M1. An adhesive failure pattern similar as that of mixture M1 was observed, see Fig. 15 (b). Different from mixture M1 and M2, the number of printed layers for mixture M3 was quite lower, with a maximum value of 3. During the printing of the fourth layer, the plastic nozzle invaded into the fresh cementitious material for around 10

mm, indicating a large deformation of printed layers due to the relatively low shear resistance of the fresh cementitious material. In addition, the fracture initiated and propagated inside the bulk of the first printed layer, indicating a cohesive failure of the fresh cementitious material.

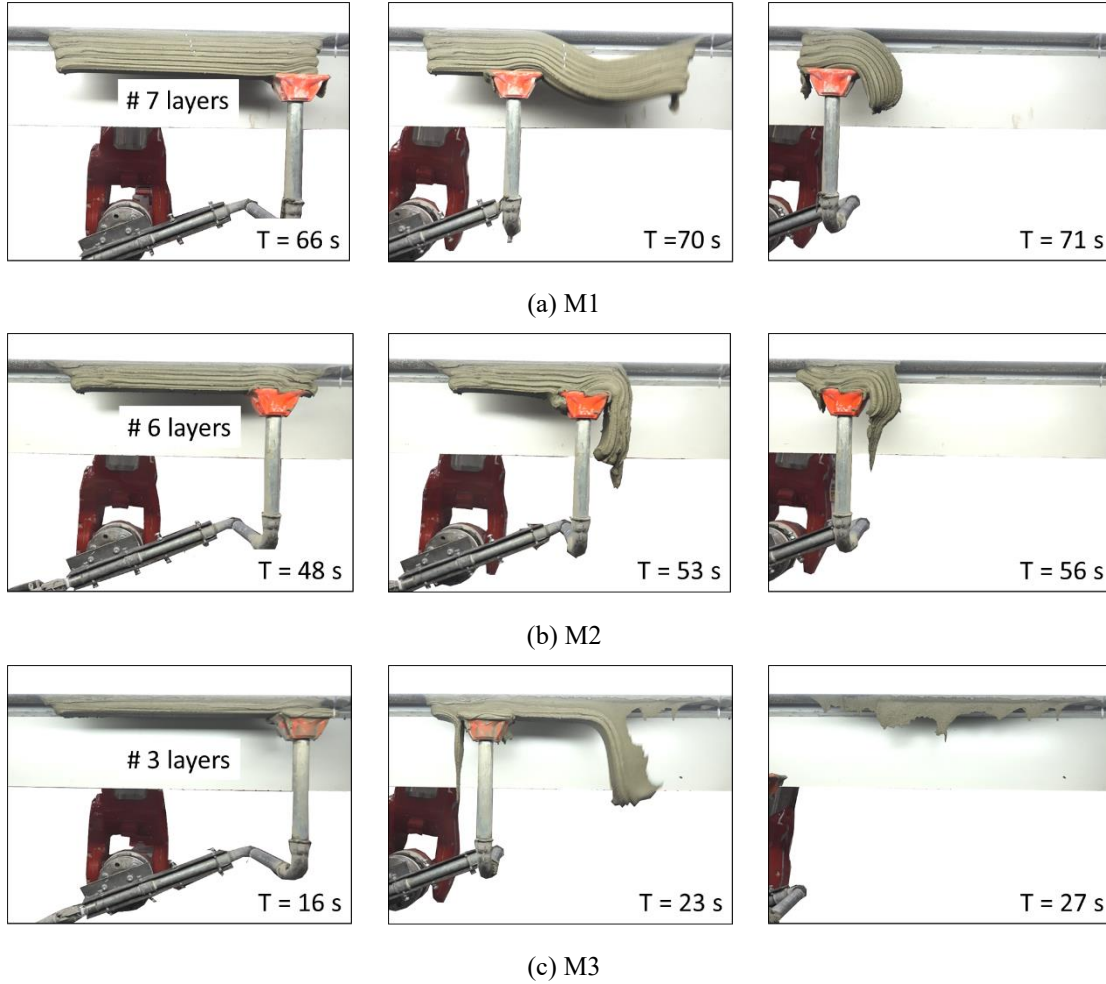
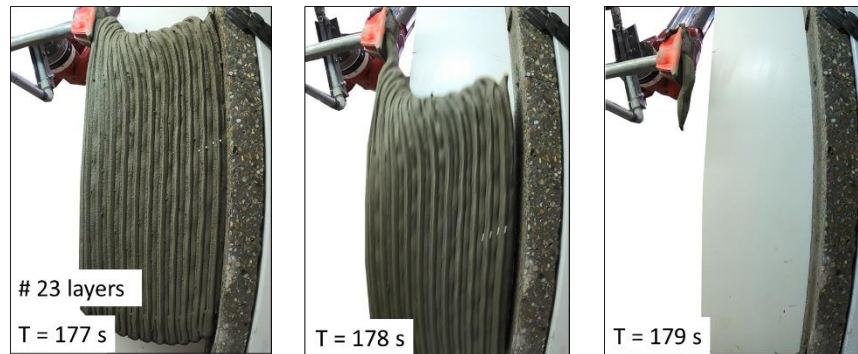


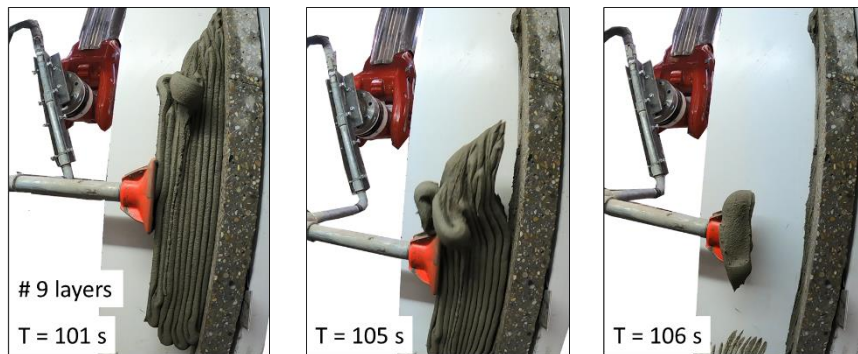
Fig. 15 3D concrete printing at the overhead position.

The results of 3D concrete printing tests at the side position are shown in Fig. 16. For each mixture, one of the three representative repetitions is presented including the maximum number of 3D printed layers (left), the occurrence of failure (middle), and the moment after failure (right). The number of the printed layers reached 23, 9, and 4 for mixture M1, M2, and M3, respectively, demonstrating a higher adhesion towards the substrate when compared with that at the overhead position, especially for mixture M1. Upon visual observation, the results showed a different failure pattern of sliding under gravity. From mixture M1 to mixture M3, the deformation of printed layers became more pronounced,

which can be attributed to the difference in the shear resistance of the fresh cementitious material. Moreover, in the case of mixture M1, a large eccentricity of the gravity center of printed elements led to a tensile stress perpendicular to the vertical substrate, resulting in a detaching from the vertical substrate. This is captured in the images of the failure moment at 178 s for mixture M1 and the failure moment at 105 s for mixture M2. As for mixture M3, due to a limited number of printed layers, the layers didn't undergo such a detaching process.



(a) M1



(b) M2



(c) M3

Fig. 16 3D concrete printing at the side position.

The maximum number of 3D printed layers of each of the three mixtures (i.e. M1, M2, and M3) at the overhead position and the side position are shown in Fig. 17. In both cases, with a decrease of the shear resistance of the fresh cementitious material from mixture M1 to mixture M3, the maximum number of printed layers tended to decrease. Specifically, for the side position, the maximum number of printed layers decreased from an average value of 22 to 3, while a change from 8 layers to 4 layers was observed at the overhead position. It was clearly illustrated that the fresh cementitious material printed at the side position achieved more printed layers, particularly for mixture M1 and M2, indicating a stronger capacity for a thicker lining structure when compared to the overhead position. However, the resistance to failure at the side position faced a sharp decrease from mixture M1 to mixture M3, indicating the weak adhesion at the material-to-substrate interface.

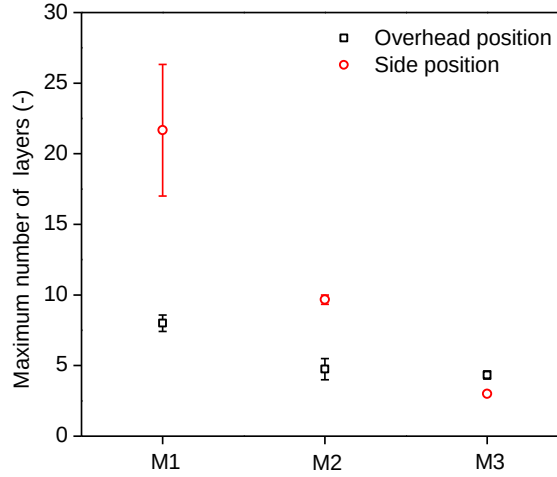


Fig. 17 Maximum number of 3D printed layers (error bars represent the standard error, $n=3$).

When comparing the detaching behavior of the fresh cementitious material, the mechanism behind the failure was different in each case. For the overhead position, more macro textures and gaps can be filled with the fresh cementitious material with lower shear resistance when applying the same pressure, which was proved in the aspect of interlayer bond in 3D printable concrete [8, 25]. As a result, more contact can be achieved with mixture M3, while mixture M1 experienced a lower contact area. The difference in the contact area and the shear resistance of the fresh cementitious material further led to different failure modes. The failure occurred at the interface for mixture M1 and M2, which can be attributed to the weak adhesion at the interface and a more solid-like behavior of the fresh cementitious material. Distinctively, the fracture propagated inside the bulk of

the freshly printed layers of mixture M3 due to the full contact at the interface and a more liquid-like behavior of the fresh cementitious material. On the other hand, the printing capacity at the side position was more related to the shear resistance of the fresh cementitious material rather than the contact at the interface. Based on the results of the shear test and the observation of the 3D printing test against the vertical slab, it can be concluded that the contact area made no difference at the side position and the shear plane initiated for each mixture in the bulk of the fresh cementitious material. Recall that the mixture type had a more significant influence on the printing capacity at the side position when compared to that at the overhead position. This indicates that the printing capacity of the fresh cementitious material at the overhead position was controlled by both the shear resistance of the fresh cementitious material and the contact at the interface, while the printing capacity at the side position was mainly determined by the shear resistance of the fresh cementitious material. As a result, only 8 layers of mixture M1 were printed at the overhead position while the side position was hardly affected by the contact at the interface (22 layers).

3.4 Stress state analysis

The stress state of the first printed layer is analyzed in this section, as schematically illustrated in Fig. 18. Several characteristic positions of the hard rock tunnel linings are depicted including the crown, shoulder, axis, knee, and invert, among which, the overhead position (i.e. crown) and the side position (i.e. axis) were specifically analyzed in this study. For the first printed layer at the overhead position, only the vertical stress σ_z (Pa) was applied perpendicular to the printed layer due to the self-weight of the subsequent layers, which can be calculated as follows:

$$\sigma_z = n\rho gh \quad (6)$$

where n is the number of printed layers at the overhead position (-), ρ is the density of the fresh cementitious material (kg/m^3), taken as 2000 kg/m^3 , g is the gravitational acceleration (m/s^2), taken as 9.8 m/s^2 , and h is the thickness of each printed layer (m).

Further, the stress along the longitudinal direction σ_y (Pa) can be calculated as follows:

$$\sigma_y = \nu \cdot \sigma_z \quad (7)$$

where ν is the Poisson's ratio of the freshly printed material (-), which is commonly assumed to be 0.3 for the 3D printed cementitious materials in the fresh state [26, 27]. Nevertheless, this value would vary when modifying the mixture composition of fresh cementitious materials.

On the other hand, the stress state of the printed layer at the side position experiences a different situation, as compared to that at the overhead position. The shear stress τ_{yz} was applied by the presence of the subsequent layers and was assumed to be uniformly distributed along the longitudinal direction (i.e. the vertical direction), which is calculated as follows:

$$\tau_{yz} = m\rho gh \quad (8)$$

where m is the number of printed layers at the side position (-).

In addition, the normal stress σ_z (Pa) in the vertical direction was induced by the self-weight of the first printed layer. In practice, the value of the normal stress σ_z was very limited as the first printed layer was also supported by the substrate with friction. Further, due to the eccentricity of the self-weight of the printed layers, a moment was induced, which further led to a tensile force or a compressive force in the horizontal direction against the vertical substrate. Accordingly, the normal stress σ_y (Pa) perpendicular to the printing direction might appear. The effect of the normal stress σ_y was more critical when more layers were printed and detaching on the upper part of the printed layers was observed, as shown in Fig. 16 (a) and (b), while for printed layers with a limited number of layers, the stress σ_y can be ignored. For example, sliding of printed layers was only observed for mixture M3, as shown in Fig. 16 (c).

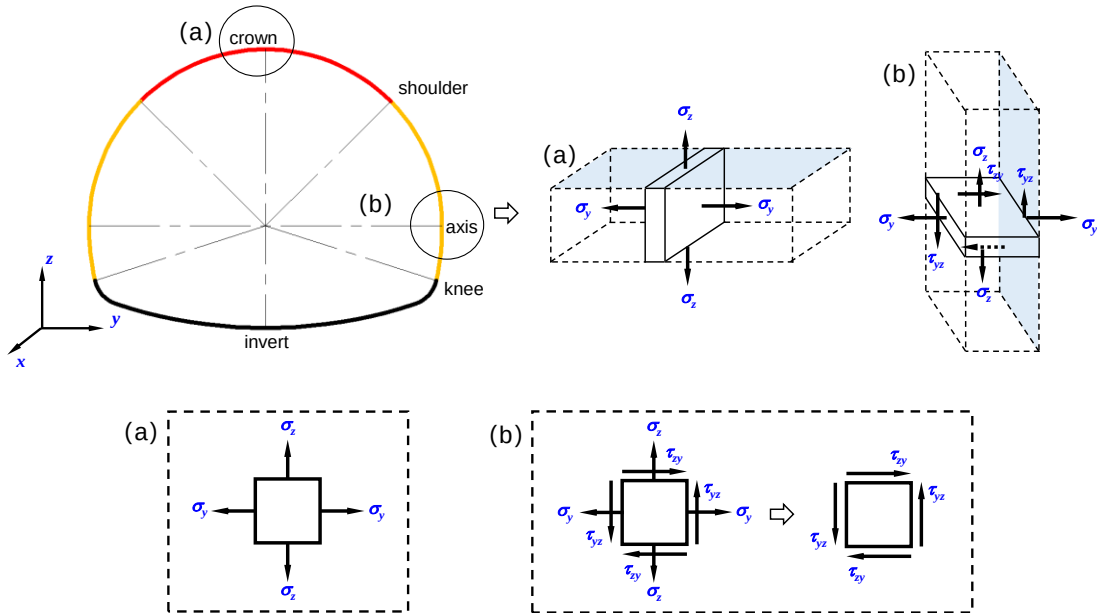


Fig. 18 Stress condition analysis of the first printed layer at the overhead position (i.e. crown) and the side position (i.e. axis).

For comparison, the tensile stress obtained in the tack test and the 3D concrete printing test (overhead position) is shown in Fig. 19 (a). In addition, the shear stress obtained in the shear test and 3D concrete printing test (side position) is shown in Fig. 19 (b). Results indicate that the stresses predicted from the tack test and the shear test fit very well with the stresses derived from the 3D concrete printing test. Therefore, it can be concluded that the tack test and the shear test are suitable to predict the capacity of 3D printed layers in both the overhead position and the side position. However, it should be noted that the prediction of other positions (e.g. the shoulder position and knee position shown in Fig. 18) is still lacking. The failure criterion of freshly printed cementitious materials will be elaborated in further studies.

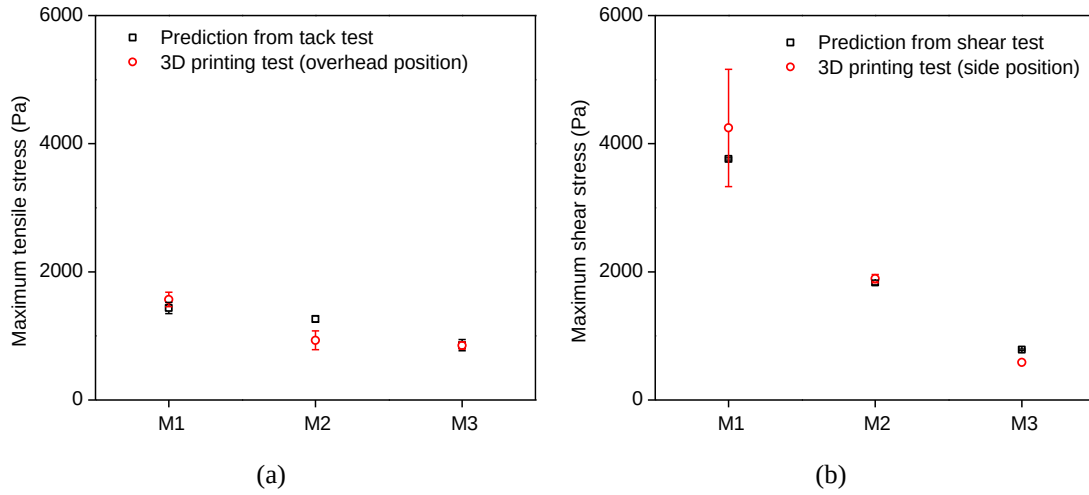


Fig. 19 (a) Tensile stress derived from the tack test (σ_t) and 3D concrete printing test (σ_z), (b) Shear stress derived from the shear test (τ_s) and 3D concrete printing test (τ_{yz}).

4 Summary and conclusions

In this research, an innovative application of 3D concrete printing for the construction of hard rock tunnel linings was developed. The adhesion of the fresh, 3D printable material, for two typical surface inclinations including the overhead position and the side position, were studied. Based on the experimental results and theoretical analysis, the following conclusions can be drawn:

- (1) The adhesion at the overhead position was limited by both the shear resistance of the fresh cementitious material and the property of the material-to-substrate interface. For a more solid-like material, less contact at the interface was obtained, leading to less friction at the interface confining the inward flow. Consequently, the adhesion at the overhead position was compromised. For a more liquid-like

material, relatively complete contact between the substrate and the fresh cementitious material was achieved.

- (2) The adhesion at the side position was mainly defined by the shear resistance of the fresh cementitious material, rather than the substrate properties. More layers were printed at the side position when compared to that at the overhead position, indicating a stronger capacity for a thicker lining structure, particularly for the mixture with a solid-like behavior.
- (3) The difference in the contact area and the shear resistance of the fresh material resulted in different failure patterns. For a more solid-like material, fracture occurred at the material-to-substrate interface which can be attributed to the weak adhesion at the interface. Adversely, for a more liquid-like material, the fracture propagated inside the bulk of the fresh cementitious material.
- (4) The stress states of the printed layers at the overhead position and the side position were analyzed. The stresses measured by the tack test and the shear test fit well with the stresses derived from the maximum number of printed layers in the 3D concrete printing test. Results indicated that the tack test and the shear test can be used to predict the capacity of 3D printed layers for the overhead position and the side position respectively.
- (5) The analysis of the stress field of the fresh cementitious materials at the interface remains an interesting point for further investigation. In addition, the development of the failure criterion for the fresh cementitious materials in a tension-shear state is worthy of studying.

Acknowledgments

The authors acknowledge the financial support provided by the Ministry of Science and Technology of China (No. 2021YFE0114100) and by the China Scholarship Council (No. 201806260248).

References

- [1] A. Parghi, M.S. Alam, A review on the application of sprayed-FRP composites for strengthening of concrete and masonry structures in the construction sector, *Composite Structures*, 187 (2018) pp. 518-534, <https://doi.org/10.1016/j.compstruct.2017.11.085>.
- [2] M.-Y. Cheng, Y. Liang, C.-M. Wey, J.-C. Chen, Technological enhancement and creation of a computer-aided construction system for the shotcreting robot, *Automation in Construction*, 10 (2001) pp. 517-526, [https://doi.org/10.1016/S0926-5805\(00\)00104-7](https://doi.org/10.1016/S0926-5805(00)00104-7).
- [3] J. Armengaud, G. Casaux-Ginestet, M. Cyr, B. Husson, M. Jolin, Characterization of fresh dry-mix shotcrete and correlation to rebound, *Construction and Building Materials*, 135 (2017) pp. 225-232, <https://doi.org/10.1016/j.conbuildmat.2016.12.220>.

- [4] M. Pfeuffer, W. Kusterle, Rheology and rebound behaviour of dry-mix shotcrete, *Cement and Concrete Research*, 31 (2001) pp. 1619-1625, [https://doi.org/10.1016/S0008-8846\(01\)00614-7](https://doi.org/10.1016/S0008-8846(01)00614-7).
- [5] L. Malmgren, E. Nordlund, S. Rolund, Adhesion strength and shrinkage of shotcrete, *Tunnelling and Underground Space Technology*, 20 (2005) pp. 33-48, <https://doi.org/10.1016/j.tust.2004.05.002>.
- [6] G. Pan, P. Li, L. Chen, G. Liu, A study of the effect of rheological properties of fresh concrete on shotcrete-rebound based on different additive components, *Construction and Building Materials*, 224 (2019) pp. 1069-1080, <https://doi.org/10.1016/j.conbuildmat.2019.07.060>.
- [7] B. Lu, Y. Qian, M. Li, Y. Weng, K.F. Leong, M.J. Tan, S. Qian, Designing spray-based 3D printable cementitious materials with fly ash cenosphere and air entraining agent, *Construction and Building Materials*, 211 (2019) pp. 1073-1084, <https://doi.org/10.1016/j.conbuildmat.2019.03.186>.
- [8] H. Kloft, H.-W. Krauss, N. Hack, E. Herrmann, S. Neudecker, P.A. Varady, D. Lowke, Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP), *Cement and Concrete Research*, 134 (2020) pp. 106078, <https://doi.org/10.1016/j.cemconres.2020.106078>.
- [9] T. Marchment, J. Sanjayan, Reinforcement method for 3D concrete printing using paste-coated bar penetrations, *Automation in Construction*, 127 (2021) pp. 103694, <https://doi.org/10.1016/j.autcon.2021.103694>.
- [10] V.N. Nerella, M. Krause, V. Mechtcherine, Direct printing test for buildability of 3D-printable concrete considering economic viability, *Automation in Construction*, 109 (2020) pp. 102986, <https://doi.org/10.1016/j.autcon.2019.102986>.
- [11] V. Mechtcherine, V.N. Nerella, F. Will, M. Näther, J. Otto, M. Krause, Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing, *Automation in Construction*, 107 (2019) pp. 102933, <https://doi.org/10.1016/j.autcon.2019.102933>.
- [12] R. Duballet, O. Baverel, J. Dirrenberger, Classification of building systems for concrete 3D printing, *Automation in Construction*, 83 (2017) pp. 247-258, <https://doi.org/10.1016/j.autcon.2017.08.018>.
- [13] Y. Shen, Y. Wang, Y. Yang, Q. Sun, T. Luo, H. Zhang, Influence of surface roughness and hydrophilicity on bonding strength of concrete-rock interface, *Construction and Building Materials*, 213 (2019) pp. 156-166, <https://doi.org/10.1016/j.conbuildmat.2019.04.078>.
- [14] C.B. Basnet, K.K. Panthi, Roughness evaluation in shotcrete-lined water tunnels with invert concrete based on cases from Nepal, *Journal of Rock Mechanics and Geotechnical Engineering*, 10 (2018) pp. 42-59, <https://doi.org/10.1016/j.jrmge.2017.07.006>.
- [15] M.A. Yazdi, E. Dejager, M. Debraekeleer, E. Gruyaert, K. Van Tittelboom, N. De Belie, Bond strength between concrete and repair mortar and its relation with concrete removal techniques and substrate composition, *Construction and Building Materials*, 230 (2020) pp. 116900, <https://doi.org/10.1016/j.conbuildmat.2019.116900>.

- [16] NEN-EN 12390-3, Testing hardened concrete — Part 3: Compressive strength of test specimens, 2019, <https://www.nen.nl/en/nen-en-12390-3-2019-en-260976>.
- [17] J. Van Der Putten, G. De Schutter, K. Van Tittelboom, Surface modification as a technique to improve inter-layer bonding strength in 3D printed cementitious materials, RILEM Technical Letters, 4 (2019) pp. 33-38, <https://doi.org/10.21809/rilemtechlett.2019.84>.
- [18] BS 1134, Assessment of surface texture. Guidance and general information, 2010, <https://webstore.ansi.org/standards/bsi/bs11342010>.
- [19] A. Kaci, R. Bouras, V.T. Phan, P.A. Andréani, M. Chaouche, H. Brossas, Adhesive and rheological properties of fresh fibre-reinforced mortars, Cement and Concrete Composites, 33 (2011) pp. 218-224, <https://doi.org/10.1016/j.cemconcomp.2010.10.009>.
- [20] S. Kawashima, M. Chaouche, D.J. Corr, S.P. Shah, Influence of purified attapulgite clays on the adhesive properties of cement pastes as measured by the tack test, Cement and Concrete Composites, 48 (2014) pp. 35-41, <https://doi.org/10.1016/j.cemconcomp.2014.01.005>.
- [21] Y. He, X. Zhang, R.D. Hooton, X. Zhang, Effects of interface roughness and interface adhesion on new-to-old concrete bonding, Construction and Building Materials, 151 (2017) pp. 582-590, <https://doi.org/10.1016/j.conbuildmat.2017.05.049>.
- [22] K. Gadri, A. Guettala, Evaluation of bond strength between sand concrete as new repair material and ordinary concrete substrate (The surface roughness effect), Construction and Building Materials, 157 (2017) pp. 1133-1144, <https://doi.org/10.1016/j.conbuildmat.2017.09.183>.
- [23] K. Zhu, W. Jiang, L. Yu, P. Guo, Z. Yang, Deformation analysis and failure prediction of bonding mortar in external thermal insulation cladding system (ETICS) by coupled multi physical fields method, Construction and Building Materials, 278 (2021) pp. 122017, <https://doi.org/10.1016/j.conbuildmat.2020.122017>.
- [24] Y.O. Mohamed Abdelhay, M. Chaouche, H. Van Damme, The tackiness of smectite muds. 1. The dilute regime, Applied Clay Science, 42 (2008) pp. 163-167, <https://doi.org/10.1016/j.clay.2008.01.018>.
- [25] L. He, W.T. Chow, H. Li, Effects of interlayer notch and shear stress on interlayer strength of 3D printed cement paste, Additive Manufacturing, 36 (2020) pp. 101390, <https://doi.org/10.1016/j.addma.2020.101390>.
- [26] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing, Cement and Concrete Research, 106 (2018) pp. 103-116, <https://doi.org/10.1016/j.cemconres.2018.02.001>.
- [27] J. Kruger, S. Zeranka, G. van Zijl, 3D concrete printing: A lower bound analytical model for buildability performance quantification, Automation in Construction, 106 (2019) pp. 102904, <https://doi.org/10.1016/j.autcon.2019.102904>.