Weak inter-layer bonding in extrusion 3D concrete printing: a comparative analysis of mitigation techniques

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Abstract. Recently, there has been meaningful progress towards the construction three-dimensional printing (3DP) of concrete (3DCP). However, weak inter-layer bonding (ILB) in extrusion 3DCP is a constraint that can critically influence the mechanical capacities, the stability of the structures, and durability. Various techniques have been proposed to mitigate weak ILB. Though, these techniques do not systematically address the basic causes of weak ILB and display inconsistency of the results. Additionally, the scope of the testing has been rather limited. Here, an approach for the mitigation of weak ILB is proposed, as part of ongoing research. It is based on stabilizer mortars (SMs) of varying mix compositions, according to the printing time interval (TI). This study compares mitigation techniques based on the statistical analysis (Chebyshev theorem, T-test, and standard error) of the test data against a 90% confidence interval. The proposed technique demonstrated peak mitigation of weak ILB with less variation in test results at extended TI up to 120 min. Besides efficacy, the simplicity of the technique i.e. practicality of the method and the materials cost, availability, safety, and sustainability remain ideal.

1. Introduction

Three-dimensional concrete printing (3DCP) has been gaining attention for large-scale construction considering technical, economical, and environmental aspects in recent years [1-3]. The 3DCP techniques are principally based on powder bed deposition and extrusion. The extrusion 3DCP techniques seem to be more practical and popular based on economic feasibility and overall level of technological maturity [4, 5]. Extrusion 3DCP techniques may be centered on ordinary Portland cement (OPC) or geopolymer concrete [6, 7]. The defining feature of extrusion 3DCP is the automatic deposition of layers to assemble structures. The layers of 3DP concrete are connected at their surfaces by adhesion [8, 9]. Due to printing time intervals (TI) between depositions i.e. time gap effects, the resulting layer interfaces may develop severe weakness [10, 11]. The inter-layer bond (ILB) strength decreases due to a lack of intermixing because of changes in material properties, and due to effects induced by printing process parameters [12-14]. Weak ILB in 3DP concrete is a constraint that can critically influence the mechanical capacities, the stability of the structures, and durability [3, 11, 12]. Previous studies are focused on weak ILB in OPC based extrusion 3DCP, whereas weak ILB is also an issue in geopolymer based extrusion 3DCP [15].

The ILB strength is determined through the measurement of the inter-layer tensile bond strength (ILTBS) and the inter-layer-shear bond strength (ILSBS). The ILSBS is of greater practical
importance in extrusion 3DCP because it is directly related to the stability of the structures [16]. Currently, there is no standard testing approach for measuring both the ILTBS and the ILSBS in 3DP concrete [9]. Le et al first investigated the weak ILB in 3DP concrete [17]. The study showed reduced ILTBS, compared to material tensile strength (i.e. 2.3 MPa to 0.7 MPa with respect to TI of 15 min and 7 days) with coefficients of variation of 5 to 30%. Moreover, beyond the TI of 90 min, the reduction in ILB is insignificant. In another study, the ILTBS was observed to decrease by 9.9%, 14.1%, and 23.1%, at TI of 2 min, 10 min, and 1 day, respectively [18]. It is pertinent to mention here that there is a scarcity of literature focusing on ILSBS which is an extremely critical aspect of structural stability.

Researchers have proposed various techniques for the mitigation of weak ILB. However, these techniques do not comprehensively address the basic causes of weak ILB. There is a high variation in the test results (up to 45%) and a lack of consistency. Additionally, the scope of the testing was rather limited. Either these studies failed to simultaneously determine both the ILTBS and the ILSBS or the testing was limited to a TI of 15 min [9, 12, 19]. It is hypothesized that effective mitigation of weak ILB at TI exceeding 30 min would be compromised. Therefore, the authors envisaged studies focusing on mitigation of both ILTBS and ILSBS considering extended TI.

This study aims to develop a weak ILB mitigation technique for extrusion 3DCP and compare it with other techniques documented in the literature based on detailed statistical analysis. The statistical analysis is centered on the Chebyshev theorem, T-test, and standard deviation. This is to validate the proposed technique that is comprehensive in the scope of testing, effective, and displays the consistency of the results. This study will facilitate the acceptance of extrusion 3DCP techniques as a regular construction practice.

2. Background: Techniques for the mitigation of weak interlayer bonding (ILB) in OPC-based 3DCP

This section discusses the background of different weak ILB mitigation techniques documented in the literature considered for comparison purpose in this study:

Contour crafting (CC) is a form of extrusion 3DCP. An attempt was made to mitigate weak ILB through the interlocking of the layers. The ILB was reported to have been enhanced by an average of 26% [9]. CC utilizes a trowel control mechanism to shape the layers into complex geometries. Therefore this method may not be practicable across the full spectrum of extrusion 3DCP.

Ehsan et al proposed the use of a sulfur-black carbon-sand (SBCS) composite polymer mortar for enhancing ILB [19]. This study did not determine the mitigation of weak ILB with respect to TI and the results showing enhancement in ILSBS were based on simulated molecular dynamics between the CSH and the SBCS composite. Since this method relies on heating for the manufacture of the SBCS mortar so it may not be feasible for on-site large-scale construction.

Taylor et al proposed mitigation of weak ILB by effective bond area amplification through the application of OPC-based pastes at the interfaces [12]. Four pastes of different compositions were tested i.e. paste-control, paste-retarder, paste-viscosity modifying agent, and paste-superplasticizer. In this study, the TI was fixed at 15 min and the ILSBS was not determined.

3. Materials and methods

The proposed technique is based on the application of stabilizer mortars (SMs) at the interfaces through extrusion on to the surfaces of substrate layers during printing.

3.1. Selection of materials for the SMs

The binder component of the SMs is a blend of OPC and high belite calcium sulfoaluminate (CSA) cement. Cellulose fiber (CF) pulps are incorporated as internal curing (IC) agents. The CF retains water for IC, aids hydration and mechanical anchorage, and helps to reduce shrinkage. The CSA cement consumes excess surface water, acts as a binder for the CF, and permits matching of the elastic modulus between the overlaying and substrate concrete layers.
3.2. Mix proportions of the SMs
The SMs mixes were designed according to TI i.e. 60 min, 90 min, and 120 min. Therefore, the proportion of the CSA cement in the blends was increased consecutively; however, it was restricted by the setting time of the blends [20, 21]. Three (03) conservative water/binder (w/b) ratios i.e. 0.45, 0.47, and 0.49 were selected to ensure the utilization of excess water from the surfaces of the fresh 3DP concrete layers [22]. The SM mixes were designated SM-1 through SM-12. Control specimens being exactly similar to test specimens but without SMs, those were designated SMC, SMC-60, and SMC-90 respectively. For SMC specimens the TI is taken at ~3 min.

3.3. Methods
3.3.1. Consistency of the SM. The effectiveness of the SMs is based on their flowability [12, 21, 23]. The consistency was quantified by the mini-slump test [24].

3.3.2. Printing of test specimens. SM coatings ~1 mm were extruded onto the top surfaces of 3DP concrete layers through a manual extrusion device immediately after extrusion. Then overlaying layers were printed at TI of 60 min, 90 min, and 120 min. The specimens were cured under ambient conditions for 28 days prior to testing.

4. Results and discussion
4.1. Comparative analysis of weak ILB mitigation

4.1.1. Comparative analysis of weak ILTBS mitigation A comparative statistical analysis was performed on ILTBS test data from four studies including one pertaining to geopolymer 3DP concrete, as presented in Figure 1 (a). The comparative statistical analysis of the weak ILTBS mitigation test data from two studies (TI of 15 min) mentioned (in Section 2), is presented in Figure 1 (b).

![Figure 1](image-url)

**Figure 1.** ILTBS; (a) statistical analysis of comparative ILTBS test data; (b) comparative statistical analysis of weak ILTBS mitigation test data, based on [11], [14], [15], [12], and [19].

From Figure 1 (a), it can be seen that overall, ILTBS varies from ~1.4 MPa to about 0.25 MPa, between TI of 1 min to 30 min, with a coefficient of variation of ~40%. The two mitigation techniques enhanced ILTBS by 59% and 100% i.e. to 0.43 MPa and 1.5 MPa respectively for a TI of 15 min [12, 19]. The ILTBS mitigation results show a variation of ~20%. Statistical analysis of the mitigation of weak ILTBS at 60, 90, and 120 min TI, based on test data of the proposed technique is presented in Figure 2. At each TI the optimal mixes i.e. SM-2, SM-6, and SM-10 have been considered.
Figure 2. Statistical analysis of weak ILTBS mitigation test data through the use of SMs.

At 60 min TI, the ILTBS was enhanced to 1.91 MPa i.e. marginally exceeding that of the control (SMC), while exceeding SMC-60 (i.e. control at 60 min TI) by approximately 32%. At 90 min TI, the ILTBS was measured at 97% of SMC. At 120 min TI, the ILTBS was enhanced to 96% of SMC and by 185%, as compared to SMC-120. Based on standard error, the test results show a 20-45% variation. Overall, this technique offers superior weak ILTBS mitigation, as compared to the other discussed techniques.

4.1.2. Comparative analysis of weak ILSBS mitigation

Statistical analysis was performed on ILSBS test data from one study, as presented in Figure 3 (a). The comparative statistical analysis of weak ILSBS mitigation simulation data from the study discussed (in Section 2), is presented in Figure 3 (b).

Figure 3. ILSBS; (a) statistical analysis of ILSBS test data; (b) statistical analysis of weak ILSBS mitigation simulation data, based on [16], and [19].

Figure 3 (a) shows that ILSBS varies from ~3.6 MPa to 2.60 MPa between TI of 15 sec to 24 h, with a coefficient of variation of about 25%. Based on simulation results (Figure 3 (b)), the ILSBS has been enhanced to 1.4 GPa [19]. Therefore, the validity of the simulation data must be confirmed by experimentation. Furthermore, the mitigation of weak ILSBS was not considered with respect to TI. Statistical analysis of the mitigation of weak ILSBS at 60, 90, and 120 min TI, based on test data of the proposed technique is presented in Figure 4.
Figure 4. Statistical analysis of weak ILSBS mitigation test data through the use of SMs.

At 60 min TI, the ILSBS was measured to marginally exceed that of SMC by 5%, and exceeding SMC-60, by approximately 40%. At 90 min TI, the ILSBS was measured at 94% of SMC. At 120 min TI, the ILSBS was enhanced to 72% of SMC and by 181%, as compared to SMC-120. Based on standard error, the test results show ~30% variation. Again this technique offers effective weak ILSBS mitigation.

5. Conclusion and recommendations
The proposed technique has significantly improved the ILTBS and ILSBS in comparison to other mitigation techniques discussed in this study with special attention to extended TI. At a TI of 120 min, the proposed technique enhanced ILTBS to within 4% of the control strength. The ILSBS was enhanced by 181%, as compared to the control at TI of 120 min. The statistical analysis of the other, weak ILB mitigation techniques show high variation in the test data against a 90% confidence interval; this could seriously question their practical implementation. The proposed technique exhibits greater homogeneity of test data and the validity of the test procedure. Simple manufacturing, the use of cheap, safe, and sustainable materials, plus possible additional benefits, marks this technique as particularly feasible for OPC based extrusion 3DCP.

Based on the evaluated data, the following recommendations are drawn:
There is an urgent need to develop standard testing approaches for the measurement of ILB i.e. both ILTBS and ILSBS in 3DP concrete.
Techniques for the mitigation of weak ILB in geopolymer based extrusion 3DCP must be proposed.

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