Mechanical Performance of 3-D Printed Concrete Containing Fly Ash, Metakaolin and Nanoclay

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Abstract. Similar to conventional concrete, the use of supplementary cementitious materials (SCMs) in 3-D printing concrete (3DPC) can be technically and environmentally beneficial. 3DPC consumes larger amount of Portland cement compared to conventional concrete so replacing the cement with SCMs will reduce the carbon footprint of 3DPC. However, it is important that the level of replacement does not lead to a significance loss of the mechanical performance of 3DCP. Therefore, this study investigates the mechanical strengths of 3DPC with various mix compositions. Mixes containing fly ash, metakaolin, nanoclay, and combination of them were studied. The test program includes measuring the compressive strength and flexural strength on standard cubes/prisms as well as 3D printed cubes/prisms at 7 and 28 days. The findings showed that fly ash decreased the early age strengths but led to an increase in the late age strengths. On the other hand, metakaolin and nanoclay did not remarkedly affect the strengths. It was found that mixes containing both fly ash and metakaolin showed better performance. Finally, it was observed that samples from 3D printed concrete had lower strengths compared to the same mixes poured in standard cubes and prisms. Optimisation of the mix compositions using these SCMs is required to achieve acceptable mechanical performance.

Keywords: 3D printing concrete · Fly ash · Metakaolin · Nanoclay · Supplementary cementitious materials

1 Introduction

The interest in 3D concrete printing (3DCP) has exponentially increased in the last decade [1, 2]. Thanks to the competitive benefits this technology can offer to the construction industry such reducing construction time, cost and waste. Various mineral and chemical additives can be incorporated in 3DCP [3]. Conventional supplementary cementitious

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materials (SCMs) such as fly ash and metakaolin are usually incorporated in 3DCP mixes and their effects on the properties of 3DCP have been reported [4–6]. However, much less research was conducted on the use of nanoclay (NC) on 3DCP. Previous research showed that NC improved the compressive strength and the interfacial transition zone in cement composites [7, 8]. Therefore, this study investigates the effect of fly ash, metakaolin and nanoclay on the mechanical strengths of hardened 3D printed mortars. In addition, previous research concerned on mechanical strength of 3DCP was based on taking standard cubes/prisms to test them. However, the emphasis in this study is on considering testing cubes/prisms from the printed mortar.

2 Materials and Methods

2.1 Materials and Mix Proportions

The cement used was Portland cement type CEM I 52.5 N, conforming to BS EN 197-1:2011 [9]. Fly ash (FA), conforming to BS EN 450-1:2012 [10], was obtained from Scot Ash Ltd. This material had a surface gravity of 2.21 and a % passing 45 μm sieve of 85%. Metakaolin (MTK) is used in this experiment to replace some of the cement. A sand of a maximum particle diameter of 1.18 mm was used.

The sand/binder and water/binder ratios were kept constant for all mixes at 2 and 0.5 (i.e. 305 kg/m^3) respectively. The water temperature was maintained at around 16 ± 1 °C for all mixtures. The mortar temperature following the end of mixing was maintained at 20 ± 2 °C.

Superplasticizer based on a polycarboxylate polymer solution, having a specific gravity of 1.07 g/ml, was used. The dosage of total SP mass was between 0.2 and 0.4 wt.% of the binder. Purified palygorskite nano-clay (PPNC) is used as a mineral VMA to control stability and flow of the fresh state, trademarked as Acti-Gel 208. The Acti-Gel 208 used is a highly purified magnesium aluminum silicate that is self-dispersing and was added at 5 and 7 kg/m^3 in the mix. Natural fibres (NF, Sisal) were also used. These fibres were added to the blend at 3.6 kg/m^3 (0.6% of binder and approximately 2.37 l/m^3 of the total mix). The mix design of all mixes tested for 3D printing are presented in Table 1. More

Table 1. Mixture proportions of mortars, kg/m^3

Mix ID	CEMI	FA	MTK	Water	NC	SP
REF NF3.6	607	0	0	1230	0	0.136
FA30-SP0.2-NF3.6	435	172	0	1205	0	1.213
REF MTK15-SP0.44	516	0	91	1210	0	2.671
FA30-MTK10-SP0.44-NF3.6	364	182	61	1180	0	2.671
FA30-MTK15-SP0.44-NF3.6	334	182	91	1180	0	2.671
FA30-SP0.2-NF3.6-VMA5	425	182	0	1190	5.0	1.214
FA30-SP0.2-NF3.6-VMA7	425	182	0	1185	7.0	1.214

information on the chemical and particle size distribution of the raw materials as well as mixing and printing procedure is detailed in [4, 11].

2.2 Testing Procedure

For each mixture, the compressive and flexural strength were tested. Compressive strengths were tested on laminated cubes and standard cubes (50 × 50 × 50 mm). The flexural strength was evaluated with 1- and 3-layer prisms and on standard prisms (50 × 50 × 200 mm). Compressive and flexural strength were tested at 7 and 28 days after casting.

For each mixture, 6 standard cubes were prepared. The mortar was placed in the moulds and compacted for 5 s on a vibrating table to ensure compaction. The excess mortar is then removed. The cubes are then removed from the mould and the samples are placed in water at a constant temperature until the test days.

Compressive strength is also important to calculate from printed cubes. This allows a comparison between uncompacted printed mortar cubes and standard compacted cubes. The moulds used in this experiment were cubic moulds of internal dimensions of 36 × 36 × 40 mm. To create these laminated cubes, 4-layer prisms are printed as shown in Fig. 1. The moulds are then applied vertically to the layers and the excess surrounding mortar is removed. These moulds are demoulded after about one hour. The only problem with this practice was that the upper and lower surface of the cubes were not perfectly smooth. Therefore, all laminated cubes were capped before placed in the compression machine.

Fig. 1. Process for developing layered cubes

The flexural test consists of a three-point bending test: the prism is positioned on two support points, 110 mm apart. The load is applied to the central point of the prism. The bending strength is evaluated at a constant load speed of 40 N/s.

Two types of prisms were tested: standard prisms according to the standard and n-layer prisms printed with the compressed air gun. After oiling the mould, the mortar is introduced into the mould and compacted on a vibrating table. The excess mortar on the surface is then removed and the samples are covered for 24 h. The specimens were immersed in water at a constant temperature until the appropriate test date. The same treatment was applied to printed samples that are extruded by the gun. These are composed of 1 and 3 layers.

3 Results and Discussions

3.1 Compressive Strength of Standard and Layered Cubes

The compressive strength of all mixes presented in Fig. 2 shows that the compressive strength increased for all mixes with time. The addition of FA reduced the strength at both ages. The pozzolanic reaction of FA is known to start at later ages and contributes to improving the strength at ages beyond 28 days which was not tested in this research. The use of metakaolin slightly reduced the strength at 7 days but had no impact on the strength at 28 days when compared to the reference mix. When the FA mixtures incorporate MTK or NC (VMA) the strength did not change significantly at both ages.

It is noted that the strength of the 3D printed concrete mixes remarkedly lower than their counterparts of standard cubes. The reduction in strength ranged between 40–52% at 7days and 12–57% at 28 days. This can be attributed to the preparation method of the 3D printed cubes which were neither vibrated nor compacted. Therefore, large number of voids and entrapped air were observed in these cubes, leading to reduction in strength.

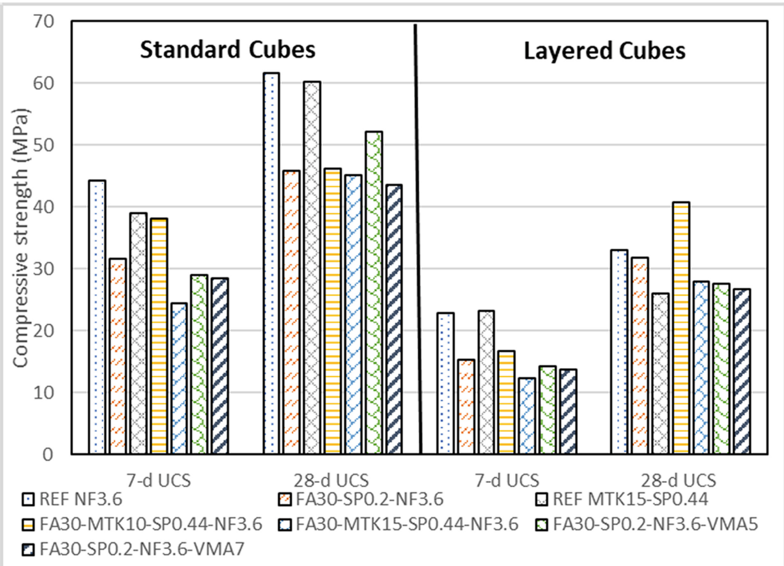

Fig. 2. Compressive strength of standard and layered cubes at 7 and 28 days for all mixes

The trend in the strength development and the effect of the FA, MTK and nanoclay were similar to that in standard cubes. However, a distinctive increase in 28-d strength was observed for mix FA30-MTK10-SP0.44-NF3.6.

3.2 Flexural Strength of Standard Prisms

The flexural strength of standard prisms did not change significantly with time as shown in Fig. 3 with slight increase in strength. However, unexpectedly, mix FA30-SP0.2-NF3.6-VMA7 exhibited lower flexural strength at 28 days than 7 days. This can be due to human error during the test.

FA decreased the flexural strength after 7 days but had insignificant impact of flexural strength after 28 days. On the other hand, MTK and NC (VMA) had no noticeable effect on the flexural strengths at both ages.

The flexural strength of 1-layer and 3-layer 3D printed prisms is shown in Fig. 3. The mixes gained comparable or better strength than those of standard prisms. However, it was clear that there was inconsistency of the results and a clear conclusion cannot be drawn from these results. The results indicate that the flexural strength of 1 layer is higher than those of 3 layers. This can be explained by the fact that 3-layer 3D printed prism had more entrapped air and cold joints, thus it is more heterogeneous and weaker than 1-layer 3D printed prism.

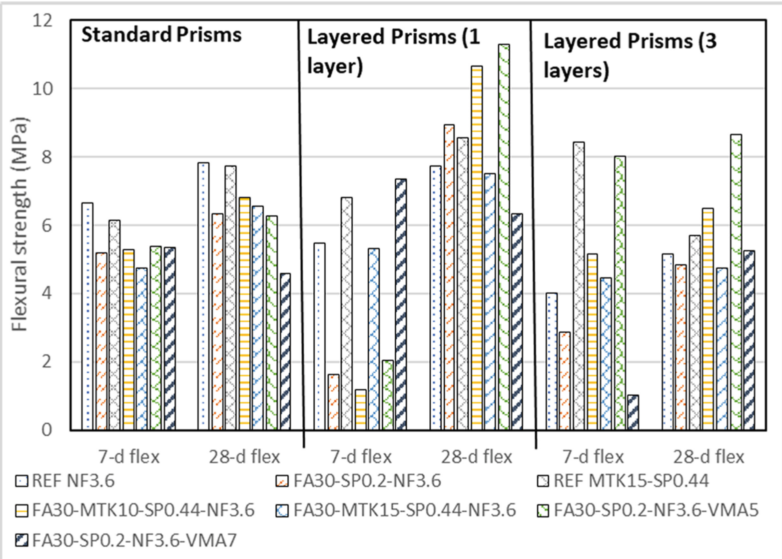

Fig. 3. Flexural strength of standard and layered cubes at 7 and 28 days for all mixes

4 Conclusion

This mechanical strength, in terms of compressive strength and flexural strength, of 3D printed mortars was the main focus of this study. The effect of different additives was explored. Understanding the influence of preparing the testing specimen in standard practice and 3D specimen was established. The main findings indicate that the replacement of cement by 30% FA lowered the strengths, particularly at early ages while the use of MTK and NC did not change the strengths. Standard cubes showed almost double higher compressive strength than 3-D printed cubes while the flexural strength of 3D printed prisms were comparable or higher than standard prism. However, there were discrepancies in the results of 1-layer and 3-layer 3D printed prism. Further investigation therefore is required to elucidate this behavior.

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