MECHANICAL PROPERTIES OF 3D BIO-PRINTING CEMENT-BASED MATERIALS

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Abstract

The aim of this paper is to investigate the effect of different mix composition on mechanical properties of a printable mortar. For the mix design, two binders such as fly ash (FA), and silica fume (SF) were used with Portland cement II and sand for a water/binder ratio of 0.50. Sisal fibres (SFR), superplasticiser (SP), and viscosity modifying agents VMA composed of diutan gum and nano-clay (NC) were used in the investigation. New method was proposed to take cubes from fresh layers' mortar. The tensile strength was obtained by using dumb bell test. All results of the compressive strengths of layers were lower than the standard cast cubes of all mixes by up to 30%, this can be attributed to the fact that the layered cubes are not homogeneous and were not compacted (entrapped air).
The addition of silica fume didn't not affect too much the compressive strength. The addition of more fibres led to a slightly reduction of compressive and flexural strengths due to the air entrapped, but it improved the direct tensile strength. SP didn't affect significantly the compressive strength.

Keywords:
Sisal fibres; silica fume; superplasticiser; compressive strength; flexural and tensile strength; viscosity modifying agent

1 INTRODUCTION

3D digital construction uses additive manufacturing techniques, which means objects are constructed by adding layers of material. Conventional approaches to construction involve casting concrete into a mould (known as formwork). But additive construction combines digital technology and new insights from materials technology to allow free-form construction without the use of formwork. Eliminating the cost of formwork is the major economic driver of 3D concrete printing. Built using materials such as timber, formwork accounts for about 60% of the total cost of concrete construction. It's also a significant source of waste, given that it will be discarded sooner or later. According to a 2011 study, the construction industry generates 80% of total worldwide waste.

Pouring concrete into formwork also limits the creativity of architects to build unique shapes, unless very high costs are paid for bespoke formwork. Free-form additive construction could enhance architectural expression. The cost of producing a structural component would not be tied to the shape, so construction could be freed from the rectangular designs that are so familiar in current building architecture.

Besides, 3D printing in building structures without formworks permits to improve the construction rate and open to new architectural liberties. Replacing humans work by additive technology automated allows building in polluted zones or on planets as we can see with the project of contour crafting with the construction of bases on the moon for the NASA. Several applications were reported on applications and prototypes of 3D printing [Khoshnevis 2006] [Alec 2016] [Scott 2015] [Alec 2016] [Lloret 2015].

Company has been able to print 10 full scale houses in less than 24 hours with 3D printing concrete. Their method is appealing by the low cost of each house, around 5000$ [Malaeb 2015]. The largest 3D printer has been created by the World's Advanced Saving Project launched in 2010 by the Italian Centro Sviluppo Progetti Company. It was 12 meters tall in a hexagonal shape [Wangler 2016].

The printability of fresh cement based materials is the ability of the layer to maintain itself and the weight of the layers subsequently deposited. The time gap between two deposited layers must be sufficiently long to provide adequate mechanical strength capable of sustaining the weight of the subsequently deposited layers and also short enough to provide an optimized bond strength and building rate. It appears that it's the shortest time gap which allows the stability of the structure during construction. The ability of the first layer to support itself and others layers is link to its rheology and more precisely to its yield stress [PER 2016] and elastic modulus [WOL 2018].

The aim of this study is to evaluate the effect of different mix composition on mechanical properties of printable mortar such as the compressive strength, flexural strength and tensile strength.

2 EXPERIMENTAL PROGRAMME

Fresh properties of printed cement-based mortar compose of fly ash and silica fume, incorporating sisal fibres (SFR), water-soluble viscosity modifying agent (VMA such as diutan gum, nano-clay) and superplasticiser were investigated.

The following properties of the mortars were examined: the slump flow, the penetration test, the rheological properties (yield value), and the extruded property, the compressive strength, flexural strength and direct tensile strength.

2.1 Materials

The mortars were prepared with a fixed water-to-binder ratio (w/b) of 0.50. Portland cement CEMI 42.5N specified by BS EN 197-1: 2000 (specific gravity of 3.13) was used in all mixes. Fly ash from Scot ash ltd was added and conformed to BS EN 450-1:2005. Undensified silica fume (SF) were used with a percentage of 8% relative to the mass of cement. The percentage of SiO_2 in SF was more than 90% and the specific surface area of SF was 17,500 m^2 /kg with a specific gravity of about 2.2.

A synthetic polycarboxylate polymer-based superplasticiser (SP) with solid content of 30% and specific gravity of 1.05 was used.

Diutan gum was supplied by Kelco-crete which is an anionic polysaccharide gum as used as viscosity modifying admixture (VMA). It was used as powder at 0.05% (by mass of binder).

A second VMA Actigel 208 Nano-clay based VMA (NC) composed of attapulgite-clay small needles with negative charges is used at 0.10% (by mass of binder).

Sand with maximum particle size of 1.18 mm was obtained sand was used in this investigation. Sisal fibres (SFR) supplied by Azichem Ltd (Italy) were used for this investigation have a length of 15 mm. Monofilament sisal fibres are used to improve cohesion, holding, mould-ability, and to limit the cracking of cementitious composites.

2.2 Mixing and testing procedure

The mortars were prepared high-shear Hobart mixer in 2-L batches. Premixed solid components, i.e. cement, fly ash, or silica fume and sand, were mixed for 30 seconds at low speed (140 rpm). Next, water at temperature of 16 ±0.5 °C and SP were added together to the mixer and mixed for 30 seconds at a low speed (140 rpm). Then the mixer was stopped, any lumps of solids were crushed, fibres and VMA1 or NC were added (within 1 min), and the paste/mortar was mixed again for 2 min (4 min when VMA2 is added) at a high speed (285 rpm). Then VMA1 is added and the mortar is mixed 1 min at a low speed (140 rpm). At this stage, the mortar mixtures were tested for rheological characteristics, as described in section on test methods. The temperature of the mortar after mixing was 20 ± 1 °C. For all tests the timing is given from zero time – that is, the time when the cement particles first touch the mixing water.

The penetration test (cone plunger) was started at 6 min (immediately after the end of mixing Fig. 1). After filling the cone mould with mortar in two layers, the cone plunger is adjusted in order to allowing the cone to just touch the surface of the mortar sample. Then the cone plunger is released allowing the plunger to penetrate into mortar paste under its own weight for 5 seconds. After 5 seconds, the penetration value is noted to the nearest millimetre.

Then the slump flow test was started at 10 min (Fig. 1). The cone-shaped mould was placed in the centre of a jolting table. After filling with mortar in two layers, the cone was gently lifted 15 times (approximately 30 s after finishing of placing of the grout). When the flow stopped, the spread of the mortar was measured with a ruler in two perpendicular directions. Finally, extrudability of mortar mixes is tested with the simple modified joint gun.

The test procedure is detailed in the following steps. The mould is placed centrally on the flow table and the mortar is introduced in two layers. Each layer is compacted with ten short strokes in order to have a uniform filling of the mould. The mould is maintained in place firmly during the filling. The excess of mortar is removing with the help of a palette knife. After 15 seconds the cone is gently and vertically lifted and the height of the spread mortar is measured (Fig. 3). The fresh density of the mortar was determined in order to estimate yield stress.

Fig. 1-2: Slump flow and penetrometer tests

Fig. 3: Slump of cylinder test

For compressive strength f'$_c$, standard cubes of 50 mm are prepared for testing at 7 days. Moulds are filling in two layers; each layer was compacted with 10 strokes. The excess of mortar is skim off with a palette knife.

Additionally, new method was proposed to test 3 D printing of mortar fabricated from layers. Layered cubes are made in order to test the compressive strength of non-vibrated and non-compacted layers (Fig. 4). For this purpose, 5 to 6 layers are printed with the gun and then are cut with a cubic mould 45 mm which is removed one minute after (Fig.4).

Fig 4: Cubes taken from 3D printed layers

As the shape of the layered cube wasn't regular and surfaces aren't parallel, a cement paste was added to flatten the top surface of the cube in order to be able to load two parallel surfaces to be tested (Fig. 5). After 24h of curing, the mould of the sample and the sealed cling film are removed. Then samples are cured in water *(20 ±1 °C)* at 7 days. Samples are tested at a constant load rate of 50 kN/min.

Fig. 5: Capping of cubes taking from 3D printing layers

Flexural test

Samples are 200 mm long and composed of two layers extruded with the gun (Fig. 6). As each specimen has unique size, the measurement of the width and the depth must be done for all the samples in order to be able to determine the right flexural strength. The flexural test consisted of a three points loading of hardened mortar samples of 7 days to failure which permits to determine the flexural strength.

After 24h covered with sealed cling film, samples are cured in water for 7 days and removed from water the evening before the test. Respecting the standard BS EN 1015-11:1999, samples are tested without any shock with a constant load rate of 40 N/sec. As sometimes the sample surface is not flat, an adaptor is used in order to have a good application of the load.

Fig. 6: Flexural test of two 3D printing layers

Tensile test

New test method was proposed to test the cold joint. In this case, the dumb bell or tensile test consisted in determine the maximum tensile strength with the application of a tension force at the opposite end of the sample until failure. For each mix three samples are prepared for testing of cold joint at 7 d (Fig. 7). Moulds are filling in two steps, first the layer is extruded into the dumb bell mould. Then the extremities of the mould are filled with extra mortar without changing the shape. Samples are tested without any shock with a constant load rate of 1mm/min.

Fig.7 : Direct tensile test on the bond of two printed layers

The mix composition of all mixes is presented in Table 1. The effects of mix design such as silica fume, fly ash, dosage of SP, percentage of fibres and type of VMA on the fresh and rheological properties are reported in another paper [Rubio 2017].

Tab. 1: Compositions of all mixes made with sisal fibres (kg/m^3)

	Cement	Water	Sand	FA	SF	VMA (%)	NC (%)	SP (%)	SFR
SP SFR	463	307	1204	144	-	-	-	0.55	1.2
SP 3 SFR	463	310	1195	144	-	-	-	0.55	3.6
1/2 SP SFR	463	308	1204	144	-	-	-	0.275	1.2
1/2 SP 3SFR	463	311	1195	144	-	-	-	0.275	3.6
SF 1/2 SP SFR	432	274	1224	146	75	-	-	0.275	1.2
SF 1/2 SP 3SFR	432	278	1215	146	75	-	-	0.275	3.6
VMA SP 3SFR	463	310	1195	144	-	0.05	-	0.55	3.6
NC SP 3SFR	463	310	1195	144	-	-	0.1	0.55	3.6
NC SF SP 3SFR	463	305	1215	144	75	-	0.1	0.55	3.6

3 RESULTS AND DISCUSSION

3.1 Compressive strength

Effect of sisal fibres

It can be observed that the increase of the percentage of sisal fibres didn't influence the compressive strength for normal cubes and layered cubes (Fig. 8). However, it can be noticed a decrease of the compressive strength for layered cubes approximately 25% compared to standard cubes. It can be explained by the fact that the layered cubes are not homogeneous and were not compacted (likely has more entrapped air in mortar).

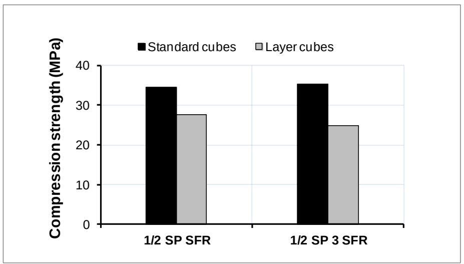

Fig. 8: Effect of dosage of fibres on f'c at 7d

Fig. 9 presents the results of the compression test of mix containing silica fume. It can be noticed no effect of SF on the compressive strength of mortar at early age. As previously stated, it can also be observed that the compressive strength of layered cubes was lower than normal cubes about 30%. It can explain by the fact that layered cubes are not compacted; therefore, they are less homogeneous and might have higher volume of entrapped air which might be increased with SF.

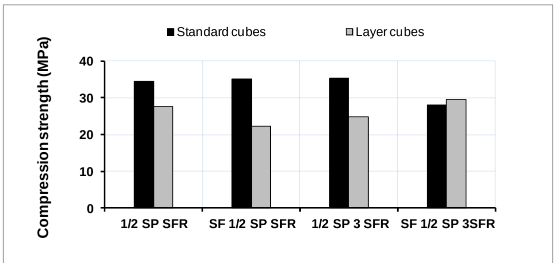

Fig. 9: Effect of silica fume (SF) on f'c at 7 d

Effect of SP

Fig. 10 shows that the compressive strength is slightly the same with a variation of SP dosage. SP dosage used didn't affect significantly the compressive strength values. However, it can be noticed again that the compressive strength of layered cubes is lower than standard cubes about 30%.

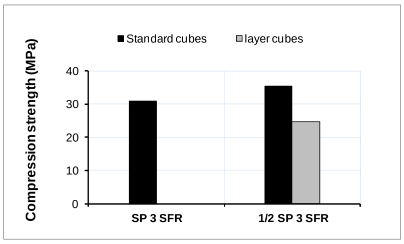

Fig. 10: Effect of SP on f'_c at 7d

Effect of VMA

For mix with the addition of VMA didn't influence significantly the compressive strength for normal cubes (Fig. 11). Similarly, a reduction of the compressive strength for layered cubes was obtained compared to standards cubes (VMASP 3SFR mix). It can be attributed to the fact that the layered cubes are not homogeneous and were not compacted (entrapped air).

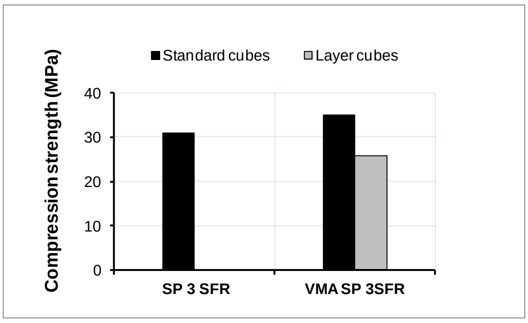

Fig. 11: Effect of VMA on f'_c at 7d

In case of addition of nano-clay (NC), it did not affect the compressive strength for normal cubes (Fig. 12). Indeed, no problems of compaction and entrapped air were noticed. Similarly, the compressive strength for layered cubes was lower than standard cubes about 25%. As the mix SP 3SFR was too fluid as previously stated, it was impossible to make the samples for the layered cube test.

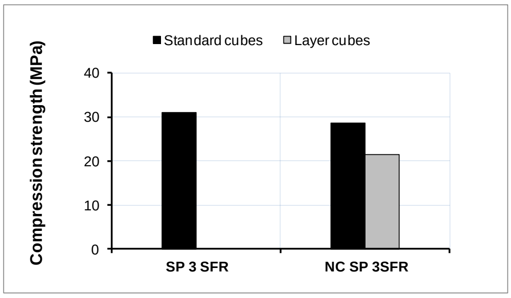

Fig. 12: Effect of NC on f'_c at 7d

3.2 Flexural and tensile strengths

Effect of silica fume

The results of flexural strength at 7 d in Fig. 13 show that adding 8% of SF resulted in a reduction of the flexural strength of layers. Indeed, standard dispersions of the results are going from 12% to 34 % for one printed layer and from 1% to 12% for two printed layers. Therefore, it is very difficult to concluded any observation on these results due to high dispersion of results.

The tensile strength shows different results because of the location of the failure and surfaces defects and air entrapped which appear with the loss of workability. However, it can be noticed that results from the tensile bond test have quite the same trend. Therefore, it might be concluded that the addition of SF induces a slight reduction of the direct tensile strength (Fig. 14).

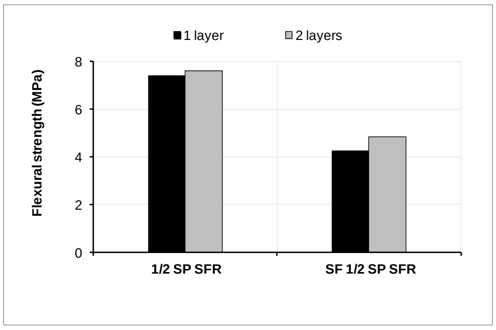

Fig. 13: Effect of SF on flexural strength at 7 d

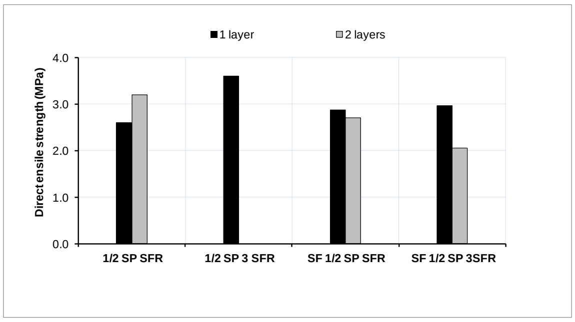

Fig. 14: Effect of SF on tensile strength at 7d

Effect of fibres

The results of the three points bending and the direct tensile tests after seven days of curing are presented in Figs 15 and 16. It can be observed that the increase of the percentage of sisal fibres causes a decrease of the flexural strength for one printed layer of 20% and an increase of the direct tensile strength of 28%. As previously stated, increasing the dosage of fibres decreases the workability and might increase entrapped air volume, surfaces defect and drainage phenomenon. It can be noticed a brittle behaviour of the material because of the type, length and diameter of fibres. Due to the large dispersion of results for flexural strength (1%-34%) and tensile strength (5%-32%) as previously stated before, more research is needed. However, the increase of fibres content led to an increase of direct tensile strength for 1 and 2 layers (Fig. 16). The results of 2 layers were slightly lower than one layer. The bond strength is greater with the increase of the dosage in sisal fibres.

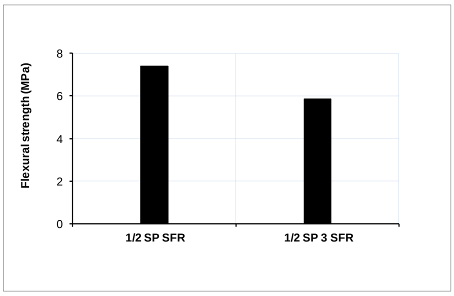

Fig. 15: Effect of fibres on flexural strength at 7d (one layer)

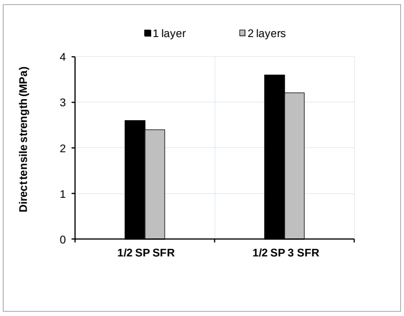

Fig. 16: Effect of fibres on tensile strength at 7 d

Effect of SP and VMA

Fig. 17 shows that the addition of superplasticiser did not affect significantly the flexural strength of one layer of mortar. In fact, the adding twice the amounts of SP led to a slightly reduction of flexural strength.

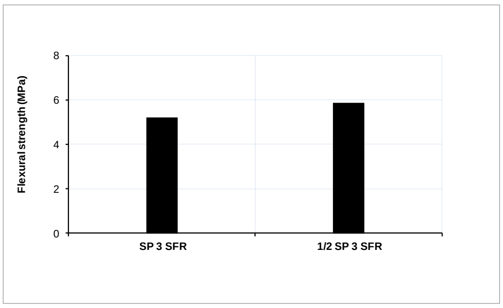

Fig. 17: Effect of SP on flexural strength at 7d (1 layer)

Similarly, the addition of VMA didn't influence the flexural strength (Fig. 18). Indeed, no problems of compaction and entrapped air were noticed of the mix containing VMA.

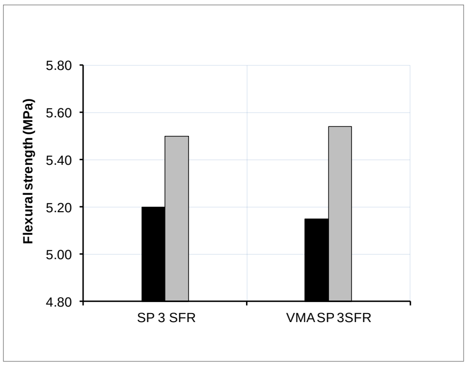

Fig. 18: Effect of VMA on flexural strength at 7 d

Figure 19 shows the results of tensile strength of mix of 2 layers were slightly higher than one layer with NC. Indeed, it can be noticed a decrease of the flexural strength with the addition of NC for one layer whereas an increase of the flexural strength is reported for 2 layers.

As the mix SP 3SFR was too fluid as previously stated, it was impossible to do the samples for the direct tensile tests.

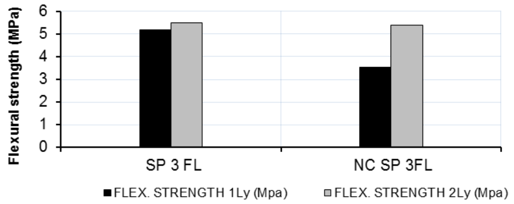

Fig. 19: Effect of NC on tensile strength at 7d

4 CONCLUSION

From this investigation on mechanical performances of 3D printing made with sisal fibres, the conclusions can be drawn:

Results from standardised for cube compressive tests, the standard deviation was lower than 10%. Moreover, the addition of VMA, NC (nano-silica) and superplasticiser didn't affect significantly the compressive strength.

Layered cubes compressive test showed similar results trend compared to the normalised cube compressive test. However, the compressive strength of layered cubes was always lower than standardised cubes in same case were about 30%. Indeed, layered cubes were less homogeneous as they weren't compacted, vibrated and were modified to have parallel surfaces.

Results from flexural test were characterised by a significant percentage of standard dispersion. As the shape of layers tested were not homogeneous, dimensions of the sample were difficult to measure and to test. It was noticed that with the increase of cohesiveness and the loss of workability, surface defects, entrapped air and drainage phenomena induced by the print process could appear and induce a decrease of the flexural strength.

Direct tensile test had the majority of its results under 20% of standard deviation with a maximum of 30% which might be more suitable compared to the flexural test results.

VMAs didn't affect significantly the tensile strength. However, decreasing the dosage of SP led to decrease the direct tensile strength up to 15%. Indeed, in decreasing SP dosage, it was noticed that with the loss of workability might led to surface defects, entrapped air and drainage phenomena induced by the print process. However, increasing SFR fibres dosage led to increase up to 30% the direct tensile strength.

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