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Building Additive Manufacturing – A Materials Evaluation

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ABSTRACT

The United Kingdom is currently in the grip of a housing crisis, a recent report from the House of Lords stated that affordable housing in Britain is a "modern plaque" that could jeopardize our standards of living for future generations. This paper aims to attempts to influence the problem of housing shortage by evaluating the potential of implementing fast Building Additive Manufacturing (BAM) as a construction process. To validate the feasibility of BAM as a building process a variety of compressive and slump tests were conducted to assess the capabilities of concrete paste as a layer-by-layer build material. A structure was fabricated to represent a FFF based BAM Process; the tests determined that nozzle design limitations, flow ability of concrete and resistance to slump are key material characteristics in constructing a house structural elements. Furthermore, the use of recyclable natural and steel wool fibres did not contribute to a mixtures compressive strength but did significantly increase its flexural strength.

Keywords: Building Additive Manufacturing, Digital Construction, Lightweight Construction.

1. Introduction

Shortage of affordable housing in United Kingdom is a rising issue due to an increasing population coupled with an increase of immigrants coming into the UK to study, live and work (Parliament.UK, 2016). The Economic Affairs Committee in its report ''Building more Homes'' states that the government must each year build 300,000 to tackle the Housing crisis (House of Lords - Select Committee on Economic Affairs 1st, 2016-2017). Due to demand for affordable housing, both the public and private sector are struggling to meet the demand several countries are researching into how 3D technologies can be best used to solve this problem.

One of the challenges is to produce a paste like material mixture, strong enough that without support will withstand the structures forces of subsequent layer addition. The limited fundamental research has emphasized the need to determine optimum and efficient mix designs for Building Additive Manufacturing (BAM).

2. Literature Review of Additive Manufacturing & 3D Concrete Printing (3DCP)M

There are advantages of 3D concrete printing technique over the conventional formwork concreting method such as labour efficiency, time, cost savings, environmental, economic impacts, and design complexity freedom (Kidwell, 2017). According to Nematollahi et al. (Nematollahi et al 2017), 3D printing technologies are mainly based on two techniques, namely extrusion-based and powder-based. Lim et al. (Lim et al. 2009) divided them into three main types; Contour Crafting and Concrete Printing, which are considered as extrusion-based process, and D-shape printing, which is a powder, based process.

Malaeb et al. (Malaeb et al. 2015) defined that the optimum mix selection criteria should be;

- Compressive strength has to be optimized while maximize the workability,
- Material has the required flow in the system yet maximize buildability upon pouring,
- Rate of concrete setting time has to be maximized while maintain the suitable setting rate to ensure bonding with the subsequent layer.

The characteristics of concrete such as flexibility, durability and non-combustibility directly contribute it to be the most extensively used construction material. Despite the fact, the conventional formwork concrete technology is restricted geometrically and has obvious sustainability issues towards the environment.

Material is the prime limiting factor in 3D concrete printing. A particular composite and concrete mixture which is denser than the typical concrete has to be used, while ensuring the mix design of concrete meets the performance requirements of both fresh and hardened state properties of concrete (De Schutter et al., 2018). Another limitation is the crucial fluctuation of material properties with unique setup and specifications of 3D concrete printer. Therefore, the major challenge is to develop a suitable printable material for corresponding printing machine (Kazemian et al., 2017).

2.1 Fresh Properties

According to Lim et al. (Lim et al. 2012), the concrete mixture should justify the following fresh state standards to be accepted as a printable material;

- Pump ability, the ability and consistency of the material to be moved through the delivery system;
- Printability or Extrudability, the easiness of the printable material through the extruder; Buildability, the ability to maintain its shape once deposited and the resistance of the placed wet material to deformation under load caused by the subsequent layers and finally the
- Open time, the period where the properties are consistent within the allowable forbearances (Roussel, 2018, Kazemian et al., 2017).
- Rheological property of fresh concrete is thixotropy. Thixotropy of a fresh material is known as the reduction in viscosity on the application of an external shear, and the gradual recovery after the shear removal (Roussel, 2006).
- The fresh properties must ensure slight or no deformation in the bead layers, with an almost zero slump but pump able concrete will be obtained. However, to develop low slump concrete, special attention is desired on the granulometric properties of the aggregates (Paul et al., 2018).

2.2 Hardened Properties

Kazemian et al. (Kazemian et al. 2017) identified the layered structures are likely to be anisotropic as voids can form between layers to weaken the structural capacity. Thus, layered concrete might create weak joints in the specimens and reduce the load bearing capacity under compressive, flexural and tensile action that needs stress transfer across or along these joints (Paul et al., 2018).

Various researchers have evaluated the bond strength with respect to the mix proportions and the vulnerability of the structures due to low strength at bond interfaces. Nematollahi et al. (Nematollahi et al. 2018), tested the effect of type of fibres on the inter layer bond strength of 3D printed geo-polymer and observed a noticeable reduction (15% to 23%) in the bond strength irrespective of the type of fibre.

3. Experimental Plan

The main aim of this research is to introduce a novel extrusion based 3D printable concrete mixture by investigating the fresh and hardened state properties, relative to the printing direction.

The following test was conducted to determine the Fresh and Hardened properties of the materials

3.1 Compression Test

Following the British Standard -EN12390-3: 2009 fourteen (14) 100 mm cubes where created and tested under compression. Each cube mixture was mixed independently, for the cubes with fibre reinforcement 800 g cement, 850 g of sand silica, 300 ml water with 1 ml High Performance Superplasticizer (Sika ViscoCrete 35RM) per 100 ml of water.

Cement and sand were mix together before mixing fibre reinforcements (if applicable), water was then added with the superplasticizer.

The mixtures were left to cure over a period of 7 and 28 days in the moulds. The environmental conditions during the curing period where set to 18ºC ± 0.5 constant temperature and 60% relative humidity.

Table 1 – Mixes Evaluated

<table>
<tr><th rowspan="2">Cubes (100 mm) Material</th><th colspan="3" rowspan="2">Fibre Reinforcement Weight (g)</th><th rowspan="2">Portland Cement (g)</th><th colspan="2">Sand</th><th rowspan="2">Water (ml)</th></tr>
<tr><th>Type</th><th>Weight (g)</th></tr>
<tr><td>1. Monofilament line</td><td colspan="3">97.6</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>2. Sisal</td><td colspan="3">50</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>3. Steel Wool</td><td colspan="3">55</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>4. Polypropylene</td><td colspan="3">63</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>5. Wool</td><td colspan="3">100</td><td>800</td><td>Silica</td><td>850</td><td>350</td></tr>
<tr><td>6. Aggregate</td><td colspan="3">-</td><td>850</td><td>Aggregate</td><td>950</td><td>400</td></tr>
<tr><td>7. Silica</td><td colspan="3">-</td><td>850</td><td>Silica</td><td>900</td><td>400</td></tr>
<tr><td>8. Building Sand</td><td colspan="3">-</td><td>850</td><td>Building</td><td>800</td><td>400</td></tr>
<tr><td>9. Plaster (100 g)</td><td colspan="3">-</td><td>850</td><td>Aggregate</td><td>900</td><td>400</td></tr>
<tr><td>10. Lime mortar (100 g)</td><td colspan="3">-</td><td>850</td><td>Aggregate</td><td>900</td><td>400</td></tr>
<tr><td>11. Wet Hay</td><td colspan="3">31</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>12. Nylon Fibres</td><td colspan="3">81</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td>13. Steel Fibres</td><td colspan="3">381</td><td>800</td><td>Silica</td><td>850</td><td>300</td></tr>
<tr><td rowspan="2">14. Tri-fibres</td><td>Hay</td><td>Nylon</td><td>Steel</td><td rowspan="2">800</td><td rowspan="2">Silica</td><td rowspan="2">850</td><td rowspan="2">300</td></tr>
<tr><td>5</td><td>27</td><td>190.5</td></tr>
</table>

3.2 Slump Test

For slump test, two procedures were used to determine the viscosity and best mixture for extrusion.

- Slump test A the use of 5280 g cement and 5610 g building sand as a constant mixture with different water ratios, the water content varied from 1400 ml to 2200 ml, nine samples measurements were taken.
- Slump test B - The second slump test was conducted using an L9 array Taguchi method. Three variables with three levels.
  1. Cement ranging from (1) 3960 g, (2) 5280 g (3) 6600 g,
  2. Sand ranging from (1) 6930 g (2) 5610 g, (3) 4290 g
  3. Water ranging from (1) 1600 ml, (2) 1850 ml, (3) 2100 ml.

3.3 Extrusion Test

For the extrusion test two different nozzles were used, the first was a circular 25mm diameter and the second had a stadium rectangular shape of 30 *10 mm, to form two lines using an extrusion system. Each extrusion had the same 45˚ angle with 5 mm height from the extruding table and roughly the same pace. Since extrusion from the mortar, extruder is not continuous but 40-60 mm per extrusion cycle. Another line was extruded to show the difference between angle and pressure height from the extruding area. Then using the best of the three samples a small wall structure was design with dimension of 700 mm length, 450 mm width 100 mm height using a stadium rectangular shape of 30 * 10 mm nozzle at 45˚ and considerable pace of 35 to 40 extrusions cycles per minute.

4. Results & Analysis

4.1 Compression Test

For the compression test fourteen 100 mm cubes were tested, ten of those where cured only for 7 days and further five had no fibre reinforcement. With steel wool and monofilament, line having the highest compression of 517 kN and 447 kN. For the 28-day curing period the Nylon and Steel fibre reinforced to achieve the highest single fibre, cube compressions of 389 kN and 417 kN accordingly.

The tri-fibre cube was created after the compression test on Wet hay, Nylon and Steel fibre reinforced cubes. For this cube 1/6 of wet hay, 2/6 of Nylon, 3/6 of Steel fibres original content was used. As shown in table one, 5 grams of wet hay, 27 grams of Nylon and 190.5 grams of steel fibre were used in the creation of Tri-fibre Cube to show the capabilities of combining fibre reinforcement in comparison to single fibre reinforcement. Highest three compressions recorded are of Tri-fibre at 649 kN, steel wool at 517 kN and sand silica at 496 kN. This shows clearly that the best mixture of Cement and sand should be with sand silica. From figure 1, we can observe that by using more than one type of fibre higher compression is achievable.

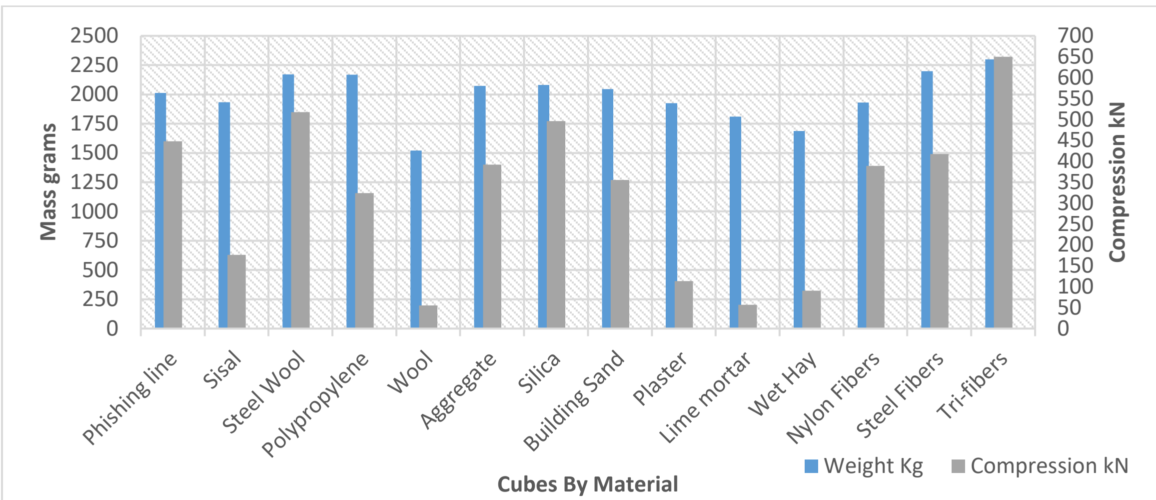

Figure 1 – Compression test of composite samples

Figure 1 were the tested cubes compression is compared to the mass in grams. Eliminating mixtures that are under 400 kN a comparison can be made to the different compressions to mass ratios. The Tri-fibres have the highest mass but also the highest compression strength with a ratio of 0.28, for steel wool the second strongest has a ratio of 0.24 the same ratio as the third strongest under compression, sand silica. Monofilament line with a ratio of 0.22 and steel fibres with a ratio of just 0.18

4.2 Slump Tests

Slump Test A - The purpose of this slump test was to determine the viscosity of a steady mixture with different water ratios. The water content increases from 1400 ml to 2200 ml with a constant increase of 100 ml per test. As the water to cement ratio increases the slump of the samples increases by 10-20 mm each time. When the threshold of water to cement ratio exits 2000 ml a dramatic and sudden increase of slump to 50-90 mm occurs.

Table 2 – Results of the slump test

Slump A	1	2	3	4	5	6	7	8	9
Cement (g)	5280	5280	5280	5280	5280	5280	5280	5280	5280
Sand (g)	5610	5610	5610	5610	5610	5610	5610	5610	5610
Water (ml) Plus Plasticizer 2ml	1400	1500	1600	1700	1800	1900	2000	2100	2200
Slump (mm)	10	20	20	40	60	70	100	150	210

Slump Test B - The purpose for this test was to produce nine different mixtures and to show which mixture had the best characteristic of low slump without having a dry mixture, which would be impractical to transport through the BAM System.

Table 3 – DOE Tests Results for slump

Slump B	1	2	3	4	5	6	7	8	9
Cement (g)	3960	3960	3960	5280	5280	5280	6600	6600	6600
Sand (g)	6930	5610	4290	6930	5610	4290	6930	5610	4290
Water (ml) Plasticizer 3ml	1600	1850	2100	1850	2100	1600	2100	1600	1850
Slump (mm) ±0.5	**90**	**110**	**230**	**70**	**100**	**40**	**50**	**10**	**20**

4.6 Extrusion Test

4.6.1 Nozzle Head

Figures 3 to 6 represents the extrusion samples using an extrusion gun fitted with either a 25 mm circular diameter or rectangular shape of 30*10 mm nozzle. The top sample represents a rectangular shape of 30*10 mm size and has the smoothest surface of all the samples.

The middle sample created with a rectangular shape nozzle with difference in angle and high to illustrate the variation and problems in design outcome when a nozzle is too close to the printing surface and the results that will occur from the angle of attack, from 45 to 90 degrees.
Figure six clearly shows the problem if the timing of extrusion at z-direction is not calibrated with the speed of the nozzle in x-direction.

Figure 3, 4. Side view, Top View

Figure 5, 6. Top view, Side View

5.6.2 Concept structure

Using the extrusion nozzle a proof of concept design was created. As shown in Figures 7 to 10 small structure was created by using an oval head nozzle at an angle of 45 degrees. The extrusion was not continuous and not even align perfectly since the capabilities of a hand-held mortar gun are limited but even with that limitation a 100 mm*450 mm*700 mm structured was printed layer by layer. The illustrations below represent the surface of the walls if there were straighten out while each layer was introduced that is creating a further outer bonding between the layers.

Figure 7 , 8– Top view of structure, Side wall,

Figure 9, 10 – Layers deposition of structure, Side view

5. Conclusions

The need of affordable housing in the U.K is a rising problem that will affect future generations. The Economics Affair Committee report in July 2016, the government must introduce measurements to tackle the ever-rising demand for affordable housing and so decrease the uncertainty in the already dysfunctional housing market. Implementation of Building Additive Manufacturing (BAM) to tackle the problem of housing using speed, reliability with reduced waste.

In this study a practical approach was taken to implement solutions and methods to extrude BAM capable materials intro a basic structure was demonstrated. The complexity of mixture design has been investigated, demonstrating that far more evaluation is required to find a solution capable of providing the BAM materials characteristics highlighted in this paper.

This paper has highlight the materials aspects required for an additive manufacturing Building system such as BAM. The research has demonstrated that the use of flow plasticiser, fibre reinforcement, sand and cement mix is critical for this application. A simple structure has been constructed which highlights the importance of materials delivery, extrusion nozzle and speed of delivery matched to extrusion velocity.

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