PRELIMINARY STUDY ON 3D PRINTING OF LOCALLY AVAILABLE EARTHEN MATERIALS IN NEW MEXICO

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Abstract

3D printing (also known as additive manufacturing) is a novel manufacturing technique that can produce complex geometries from a 3D model and minimum human intervention. The advent of 3D printing offers promises for the future of the construction industry because of its many benefits, including faster and cheaper construction, reduction of formwork, labor, and waste of materials. Most studies in this novel construction technology have focused on 3D-concrete printing; nevertheless, cement production (as the main ingredient of concrete) accounts for about 7% of total carbon dioxide emissions. Thus, cement content should be reduced or replaced by green alternatives to attain sustainability in the construction industry. On the other hand, a nonsynthetic choice such as “earthen material”, one of the oldest building materials used since ancient times for home construction, certainly offers a high potential to be 3D-printed as a construction material and build sustainable, affordable, and durable houses. Earthen material with a very low carbon footprint is a mixture of soil, sand, water, stabilizer admixture, and straw. It can be used for 3D printing of natural, durable, and sustainable walls. New Mexico (NM) is the land of earthen structures in the US, and the local soil in New Mexico has an excellent quality to be used in construction. This study presents the preliminary results of designing printable earthen mixtures using locally available soil in NM and adapting its fresh properties to construct 3D-printed walls.

Keywords: 3D printing, local soil, additive manufacturing, concrete, New Mexico

1 Introduction

3D printing (3DP) is the additive deposition of material through a computer-controlled process[1]. Charles Hull invented this technology in 1986 in a process called stereolithography[2]. In recent years, 3DP has begun to be successful to be utilized for many applications in different sectors of the industry, such as construction. 3DP has been used to build various components in the construction industry, including a pedestrian bridges[3], bus stop stations[4], and houses[5], [6]. 3DP would offer more sustainable, affordable (by labor cost savings, no framework requirement, and lowering the material waste) and safer construction (by minimizing human involvement in the semi-automated process)[7]. Additionally, it enables the construction of complex geometries with less effort. Up to now, concrete has been widely used as a material for most 3DP projects because of its flowability, formability, and mechanical performance. However, using concrete as a construction material for 3DP would question the sustainability of this construction process. To make the novel 3DP technique greener, the construction industry needs to consider the application of alternative sustainable materials instead of concrete. One of the promising alternatives is utilizing local materials such as soil for 3DP instead of concrete.

Earthen construction has become popular due to its low environmental impact and recyclability. Adobe is one of the oldest forms of structure found in various parts of the world, including the Middle East, Africa, and Europe. Moreover, adobe construction is widely used in different forms of construction in New Mexico (NM), United States. Adobe is a blend of local materials, including sand, silt, and clay, mixed with water to reach a plastic consistency; thus, it can be cast into any desired shape. Considering that using adobe and earthen materials in construction would support sustainability, in modern days, recent research has been done on utilizing traditional construction materials through automated practices such as 3DP.

Some preliminary studies of 3D soil printing (3DSP) with different soil mixtures explored the feasibility of utilizing local soil in 3DP and evaluated the fresh and hardened properties of 3D printed components[8]–[12]. In the 3DP process, the printed mass must support the self-weight and weight of the upper layers in the fresh state before its drying and hardening process. Thus, it is critical to design a flowable and buildable mixture for 3DSP[13] The soil mixture typically exhibited a weaker mechanical performance (i.e., compressive strength) than the cementitious materials in their hardened state. Therefore, designing a soil mixture with a comparable compressive would be more promising. Perrot et al. [8] investigated the use of commercial alginate, a family of seaweed biopolymers, as an admixture with the soil for 3DSP. Their printed specimen exhibited compressive strength of 1.2 MPa with the 3% alginate soil mix design. Bajpayee et al.[9] investigated the addition of sodium silicate as an admixture for the soil mix design and found the compressive strength of the cube to be about 3 Mpa. Elena et al.[10] designed a mixture of soil, lime binder, and rice husks for the mix design. The best soil mixture of the cube reached a compressive strength of 2.5Mpa. Lubin et al.[11] investigated the blend of soil and cement as the building material, and they achieved a compressive strength higher of 54 Mpa. This higher strength was achieved due to the 70% weight of cement in the mix design. Another important hardened property is related to the shrinkage of printed soil filaments, which needs the researcher's particular attention to design a printable soil mixture with sufficient strength and low shrinkage and, as such, the risk of cracking over the serviceability of the 3D printed structures.

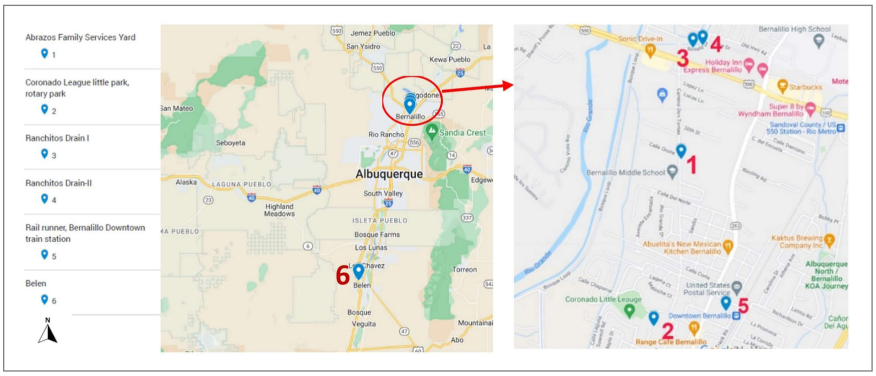

Figure 1. a) Location of soil samples at six different locations nearby Albuquerque; b) Locations of soil samples 1-5 at Bernalillo.

This paper examines the proper use of available local resources in NM for 3DSP. This preliminary study evaluates the feasibility of using NM soil collected from six different resources. After initial characterization of soil properties, the best candidate in terms of clay content, plasticity index, and soil gradation was chosen. Then, four soil mixtures were designed with the right combination of soil, lime, water, and wheat fiber as reinforcement elements to minimize the crack formation. The 7-day strength and shrinkage of cast soil specimens were determined, and the most promising mixture was used for the trial printing process.

2 Materials and Methods

2.1 Local NM soils and soil characterization

Test soils were collected from various locations near Albuquerque in NM. Six samples were collected from the north and south of Albuquerque, as shown in Fig.1. The collected soil was classified according to the ASTM D2487[14] (i.e., Unified soil classification system (USCS)). The samples were collected by removing the topsoil, which consisted of organic matter. For the soil characterization, sieve analysis was performed for fine aggregates where soil passed through a 9.5 mm (about 0.37 in) sieve. For accurate gradation, the soil was dried, and clumsy clay particles were crushed into powder.

2.2 Soil mix design and material tests

After characterization of the soil, one of the soils with acceptable plasticity and clay content was chosen for the soil mix design. Wheat straw was also used as the reinforcing material to reduce cracks in the hardened state of the materials. The wheat straw was blown, cut into smaller pieces by the leaf blower, and then sieved to the sizes less than 15 mm in length. Moreover, Type S hydraulic lime was utilized as a mix stabilizer in the soil mix design for research.

Six soil mixes were designed and shown in Table 1. The ratios in the table indicated the mass proportions (mass percent) of different components. The mixture was mixed in a Hobart mixer[15] according to ASTM 305-20[16]. The water content was adjusted according to the plasticity range measured in the soil characterization step. Because of the addition of lime and fibers, the required water content to reach acceptable formability for each mixture is different. In Table 1, S, F, and L stand for Soil, Fiber, and Lime, respectively. Furthermore, the mass percent of F and L are also displayed in the Mix ID, and

No.	Mix ID	Soil	Lime	Fiber
1	SF0L0(37)	100%	-	-
2	SF1L0(42)	99%	-	1.0%
3	SF1L2(54)	97%	2%	1.0%
4	SF1L4(58)	95%	4%	1.0%
5	SF1.5L3(54)	96.5%	2%	1.5%
6	SF1.5L4(58)	94.5%	4%	1.5%

Table 1. Mix proportions of soil mixes (mass ratios of powdery components)

the % water by weight of the total dry mixture used is also mentioned in the bracket for each Mix ID.

This paper is a preliminary phase of the study to evaluate the feasibility of the designed soil mixes that could be used for 3DSP purposes. To evaluate the compressive strength of each mix, the mechanical test was conducted according to ASTM C109-20[17] by casting three layers of fresh soil mix into 50 × 50 × 50 mm. Three cubes were prepared for each soil mix, and then the average strength was obtained within 7 days of curing under the ambient environmental conditions of the laboratory. The load was applied at 0.0393 inches per minute in the compression tests. A shrinkage test was performed to assess the shrinkage and cracks on the test specimen. A prism of 254 × 50 × 50mm was utilized for the shrinkage investigation and cracks measurement of the length of prism specimens according to ASTM C806-18[18]. The specimens were cured in the ambient conditions of the laboratory. The length change of shrinkage prisms was measured daily for up to 7 days.

2.3 Trial 3D printing test

After selecting the better soil mixture (SF1L2), a gantry-type 3D printer was used for printing with the three degrees of freedom with a frame size of 2m×2m×2m. This printing was done with a 20 mm nozzle size, a filament height of 10 mm, and a printing speed of 20 mm/sec. The soil matrix was mixed in the printer at 30 mm/sec. Two different objects (i.e., beam and pot) were printed to evaluate the printability of soil mixtures.

3 Results and Discussion

3.1 Characterization of different NM soils

Fig. 2 represents the gradation of the soils. The soil had a D60 of 0.76mm, meaning 60% of the grains were smaller than the grain size of 0.76 mm. As per USCS, it was classified as poorly graded sandy soil SP. According to the Atterberg limits, Soil 5 and Soil 6 were promising regarding the plasticity of the soil. The rest were more sand-like and non-plastic, respectively. The non-plastic soil does not have cohesive properties, which is the most important requirement for the buildability of the fresh mixture in 3DSP. Thus, Soil 1, Soil 2, Soil3, and Soil 4 were neglected. Soil 6 had a liquid limit of 52.1%, a plastic limit of 21.6%, and plasticity of 30.5%, whereas Soil 5 had a liquid limit of 20.6% and 19.3% with a plasticity of 1.3%. Soil 5 had a small plasticity range, making it difficult to control the water content on the soil-mix design. Therefore, Soil 6 was used in the research of 3DSP.

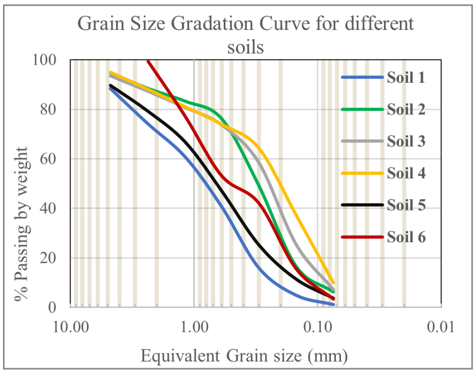

Figure 2. Grain size distribution of the soils at various locations.

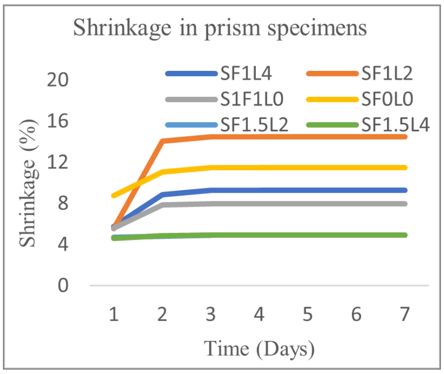

Figure 3. Shrinkage in the prismatic length of specimens.

3.2 Shrinkage of soil mixes

The shrinkage of prism specimens was tested under ambient laboratory conditions, and the shrinkage was not noticeable after 3 days. Fig. 3 illustrates the shrinkage as a function of time during 7 days. Table 2 illustrates a summary of the shrinkage test after 7 days. SF0L0 had a complete failure with major cracks in width, while SF1L0 warped. SF1L4 was also fully cracked within 24 hours of curing. The shrinkage and cracking were reduced by adding more fiber in SF1.5L2 and SF1.5L4.

Mix ID	Max crack width(mm)	Shrinkage in length (%)	Prism specimen after 7 days	Prism specimen after 7 days
SF0L0	Cracked	11.5		Failed due to cracks
SF1L0	0.28	7.8		Failed due to bowing (warping)
SF1L2	0.65	14.8		High Shrinkage
SF1L4	1.41	11.2		Failed due to cracks and warping
SF1.5L2	0.1	4.8		Acceptable (minor cracks)
SF1.5L4	0.19	4.4		Acceptable (minor cracks)

Table 2. Summary of shrinkage of the prism specimens of soil mixes.

3.3 Compressive strength of soil mixes

The compression tests for SF0L0 and SF1L0 were not successful due to cracks and warping of the specimens. Therefore, Fig. 4 displays the 7-day strength of the soil specimens. The results indicated

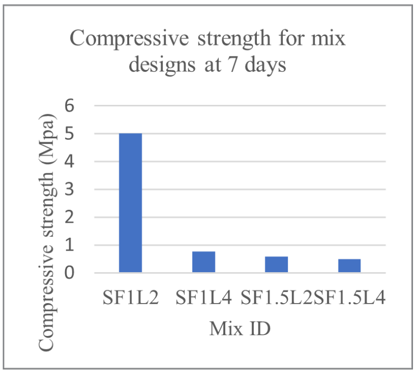

Figure 4. Compressive strength of cubes at 7 days.

although increasing the fibers on the soil mixes led to shrinkage and cracking reduction, it caused a decrease in compressive strength. The optimum lime and fiber contents led to the highest strength were 2% and 1%, respectively (i.e., the 7-day strength of SF1L2 was 5.04MPa, but it decreased to less than 1 MPa when the fiber content was increased to 1.5%). However, further investigation is required to study the effect of lime on the strength development of soil samples. When broken in the compressive specimens, the cubes for SF1L4 and SF1.5L4 were found to be dryer and less compacted than the specimens of SF1L2 and SF1.5L2.

3.4 Preliminary printing tests

The extrusion capabilities of SF1L2 were tested by printing layers of fresh soil mixtures as demonstrated in Fig. 5. The results show acceptable buildability but low printing quality, and in the next phase of this project, the printing quality will be assessed in more detail.

(a)

(b)

Figure 5. 3D printing of (a) soil beam (b) soil pot.

4 Conclusion and Future Developments

This paper is a preliminary phase of a larger proposal to use locally available NM soil for 3D printing purposes. This paper started by characterization of six different local soils and choosing the most viable one for the soil mix design process. The effects of natural fiber and lime addition were evaluated in terms of compressive strength and shrinkage. The compressive strength results indicated that the optimum values for the lime and fiber were 2% and 1%, respectively. Additionally, larger fiber content (1.5%) helped minimize the shrinkage and cracking while lowering the strength. A preliminary printing test of SF1L2 has proven to be successful in terms of buildability, but more investigation is required to improve the quality of 3D-printed filaments.

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