TRANSITION FROM TRADITIONAL COB CONSTRUCTION TO 3D PRINTING OF CLAY HOMES

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ABSTRACT

3D printing of cementitious material can provide an affordable, sustainable, and optimized approach for the construction of homes, without compromising quality or craftsmanship. While most of the current research and development efforts in this field are focused on cement-based concrete printing, this paper focuses on the current state-of-the-art literature review of designing and developing a sustainable clay-based mixture design that mainly includes clay, sand, straw, lime, and water. The goal of this paper is to bridge the gap between typical traditional earth construction, specifically cob construction, and emerging 3D printing of cementitious materials. The specific objective of this paper is to offer some possible changes in the typical cob mixture so that it can be used for 3D printing of clay-based mixtures with sufficient flowability, buildability, strength, and open time (i.e., the time period between printing of one layer and printing of another layer deposited on a layer below). The paper describes typical clay-based mixtures and their traditional process and then specifies the challenges in going from traditional cob construction to advanced computer-controlled robotic 3D printing.

KEYWORDS

3D Printing; Cob Home; Cement-Free Concrete; Earthen Construction; Concrete 3D Printing; Adobe Home; Clay-Based Mixture; Additive Manufacturing and Construction

1. INTRODUCTION

Current studies show that the building industry is responsible for almost one-third of the total greenhouse gas emissions (Arooz & Halwatura 2017, Craveiro et al. 2018, Ürge-Vorsatz et al. 2012), thus having an environmentally friendly construction material is essential. Consistent with such a view, there is renewed interest in earthen construction (Earthen Construction 2020, The Institution of Civil Engineers 2019, Runge 2020) because of its natural and environmental

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factors. Referencing Gomaa et al. (2019) and Veliz et al. (2018), Alhumayani et al. (2020) states that 3D printing (3DP) of earth-based material would have a positive effect on the environment due to the reduction of the carbon footprint, transportation, and construction waste.

As described by Gunawardena (2008), earthen construction includes many different methods. The list includes adobe as an example of a molded earth block method, cob as an example of a stacked earth lump method, and blocks or rammed earth as an example of a compacted earth method. In typical cob construction, the clay-based mixture lumps are stacked to create a monolithic wall. In some ways, this process is similar to the additive manufacturing (AM) technique used in the 3D printing of concrete (3DPC), where the mixture is pumped through a hose and exits from a nozzle as a filament into the designated location by use of a robot arm or gantry frame system. The process is repeated by extruding other layers, each placed on top of the previous layer until the desired height is reached. Both processes stack the mixture to create a structural element. The use of earth construction allows the material to be locally sourced, which reduces material transportation and thus the construction cost (Gunawardena 2008). On the other hand, the use of 3DP reduces the highly intensive labor work associated with typical cob construction. Therefore, by specializing and applying 3DP to create cob type construction, the result would be a less labor-intensive, more environmentally friendly, and highly affordable construction method. This paper provides a state of the art literature review to explain cob material's components and its process. Then, the potential of cob to be used in 3DP is explored. Moreover, the methods used to test cob's structural stability, the shortcomings of the current methods, and the current state of 3D printing of clay-based mixtures are discussed.

It is commonly known that the word cob refers to "an old English root meaning lump or round" (The Hollies Centre for Sustainability, Cob Building). However, according to Gunawardena (2008) citing Elizabeth (2000), the word comes "from the old English word for 'loaf'," which is the name used in southern England, for a type of earth construction. Cob construction is the process of using local mud to create a monolithic wall manually, without the use of formwork. Cob is usually made of clay, sand, straw, and water, which are locally sourced materials. In typical cob construction, the earth materials are mixed with water and are then lumped into masses; the lumps are then stacked on top of each other to build a monolithic wall. Based on Fordice (2017) in reference to Bati (2008), buildings with walls similar to cob walls were found in North Africa in the 11th century, while in Europe, cob construction started in the 12th century and continued to be the typical construction method until the late 1800s when it was replaced by brick masonry.

2. PROCESS OF DEVELOPING A COB MIXTURE

Cob typically consists of subsoil, fibers, and water (Reyes et al. 2018). Since cob is considered a vernacular earth construction, its material components vary. The subsoil used in the mixture must include clay (Reyes et al. 2018). On the other hand, fibers can sometimes be excluded from the mixture, i.e., fiberless cob mixtures (Hamard et al. 2016). However, cob mixtures with the use of natural fibers are more common than fiberless cob (Hamard et al. 2016). Sometimes additives are introduced to the mixture to further enhance the mixture's strength. Typically, a natural additive such as lime is used. In this section, a more detailed overview of each cob material is provided, along with the process used to mix the materials.

2.1 Cob Material

2.1.1 Subsoil

As defined by Hamard et al. (2016), cob is the process of building a monolithic load-bearing structure by gathering subsoil materials in their Plastic State, moistening them by adding water, and then shaping the wetted mixture to create a solid shape. All soils have some percentage of water content, which can affect the soil performance. Therefore, limits are introduced to set boundaries for water content percentages at which soil performance would change based on the Atterberg limits (Jamal 2017), according to which, the soil is considered to be in a Plastic State if it is in between the Plastic Limit and the Liquid Limit. The former is defined as the water content associated with the condition of soil when crumbling of rolled threads occurs (e.g., Jamal 2017). However, the latter is the second boundary of the soil's Plastic State, as it corresponds to the maximum water content at which the soil remains in the Plastic State, and that any further increase in the water content would result in the soil acting as a liquid (Jamal 2017). According to Fordice (2017), when cob mixtures that were used in existing cob structures were tested, all cob mixtures were in the Plastic State. These structures were built by experienced workers (Fordice 2017), rather than licensed engineers. Therefore, the Plastic State was achieved based on feel, which can be established by experience.

One main step in the process of developing a cob mixture is to determine the location to excavate the subsoil. Since the type of soil used in the mixture plays an important role in the cob's performance, tests were performed on historical cob buildings to determine the type of soil used. Test results showed that the earth soil next to the building had similar geological properties as the soil used in the building's walls (Hamard et al. 2016, Harries et al. 1995). Therefore, it was concluded that the subsoil used in cob construction was local soil (Hamard et al. 2016, Watson and McCabe 2011). Furthermore, according to Hamard et al. (2016), typically, the soil used had either loam, clay, silt, or clayey-silt content. As clay is a cohesive soil and is considered the binder of the material, and if it is used in low proportions, the cob mixture would be disintegrated. Considering that the amount of clay affects the cob's drying shrinkage, extensive review by Hamard et al. (2016) shows that 20% is considered the optimum percentage of clay in cob mixtures. Citing Millogo et al. (2008), Piani et al. (2018) states that the mineralogical family of the clay content plays just as important of a role in the mixture's performance as its percentage does. For example, expandable clay minerals that cause cracks but provide strength should be balanced with non-expandable clay minerals that reduce shrinkage and cohesion (Piani et al. 2018). On the other hand, the rest of the ingredients in the soil used are what equips the material with strength (Hamard et al. 2016). Lastly, the cob's strength also depends on its density. Therefore, having a well-graded soil will provide a stronger cob mixture since its particles will be able to properly fill in the voids (Hamard et al. 2016, Watson and McCabe 2011). The literature also states that the geographical location and the depth from which soil was excavated played an essential role in the soil's properties. It was concluded that the soil right below the topsoil had the best properties to be used in a cob mixture (Hamard et al. 2016).

2.1.2 Fibers

While cob and adobe bricks can be constructed with or without fibers (Hamard et al. 2016), fibers are believed to have some useful effects, including durability, controlling shrinkage cracks, or under certain conditions, increasing tensile strength. For example, according to a review of this effect by Hamard et al. (2016) considering multiple references, "Fibers provided extra tensile-strength to cob walls and improved weathering resistance, but this was true only if fibers were evenly distributed." Therefore, while there is less dispute on some positive effects of fibers, given that only under ideal conditions fibers may lead to an increase in tensile capacity, one needs to be cautious and more conservative to consider this effect. On the other hand, Piani et al. (2018) found that fibers only enhance the strength of highly sandy mixtures and that fibers tend to decrease the strength and elasticity in other mixtures. The authors interpret these findings to the bonding between fibers and soil particles in the mixture and the type and shape of the fibers used. Furthermore, the failure mechanism experienced by elements such as bricks varies with the addition of fibers in the mixture (Piani et al. 2018). For example, earthen bricks made without fibers seems to experience a brittle failure, while fiber-enriched bricks experience a more ductile failure (Piani et al. 2018). Piani et al. (2018) interpret this change in failure mechanism to the redistribution of forces in the mixture due to the addition of fibers.

Hamard et al. (2016) did a comprehensive review of cob in different countries and noted that adding fibers in cob mixtures can have multiple benefits. First, since the cob material is usually in its plastic state, adding fibers can ease the mixing process. Second, in traditional cob construction, the material is manually placed in building the wall, so there is a chance of pieces falling from a handful of lumps; thus, adding fibers can aid in keeping the lump integrated as it is carried. Third, adding fibers would result in a faster drying process. Furthermore, when it comes to the performance of the material, adding fibers would increase the material's shear resistance, enhance its durability to weathering effects, and allow shrinkage cracks to spread throughout the element, which in return would prevent the structure from having shrinkage cracks on one side (Hamard et al. 2016). Finally, adding fibers can act as a reinforcement to securely bond the material, especially at angles between walls or between successive lumps (Hamard et al. 2016). Still another advantage of fibers is to help the drying process by directing water from the interior to the exterior of the wall (Hamard et al. 2016). Piani et al. (2018) also echo this aspect that due to the efficient drying process fibers provide in the mixture, the number of shrinkage cracks is reduced. Furthermore, it is also noted that the mixture's capacity to deform is highly dependent on the fiber reinforcements used (Piani et al. 2018). Of course, while the most commonly used fiber type is straw, different materials, including hay, animal hair, wheat straw, and flax can be incorporated into the mixture as fibers (Hamard et al. 2016). Figure 1 shows the effect

FIGURE 1. Cob's strength as a function of different percentages of straw and moisture content (Adapted from Harries et al. 1995).

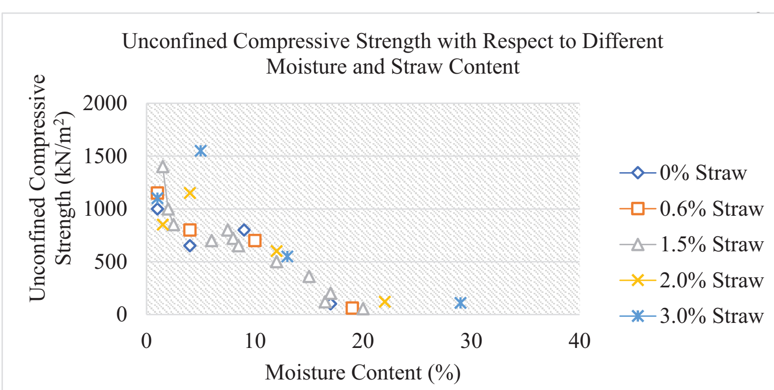
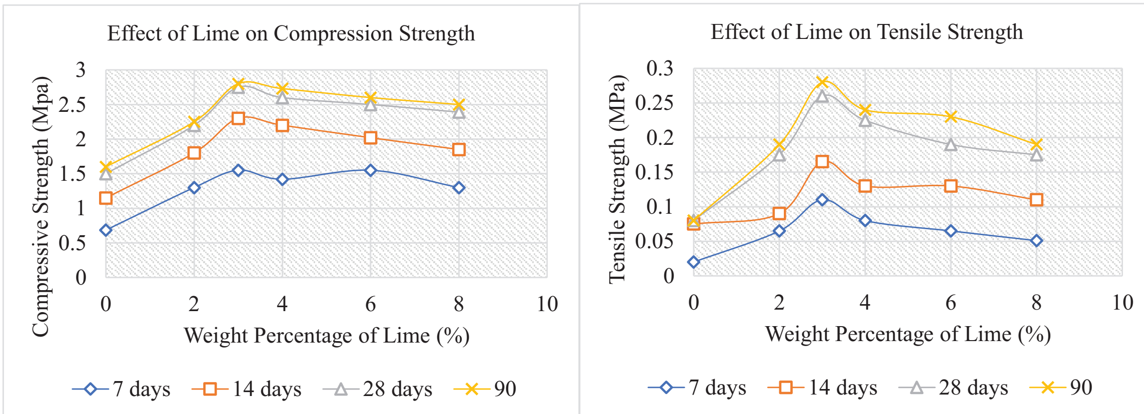


FIGURE 2. Compressive and tensile strength graphs with the corresponding lime content (Adapted from Millogo et al. 2012).



of water content and the amount of straw on the cob's strength (Harries et al. 1995). The data presented in Figure 1 shows that as the moisture content increases in the mixture, the mixture's compressive strength decrease. Furthermore, the figure also indicates that including 1.5% to 3% of straws in the mixture would increase the mixture's compressive strength. According to Harries et al. (1995), straw content needs to be within the range of 1%–2% of the cob mixture's weight to achieve optimal results in terms of a sufficient wet cob strength and reduced amount of cracks that occur due to the drying process.

2.1.3 Additives

Before the use of Portland cement in concrete, lime was used as a binder in ancient concrete mixtures (Jamal 2017). Limestone gets thermally decomposed, resulting in quicklime formation, and as quicklime reacts with water, slaked lime is formed (Jamal 2017). To achieve the slake lime cement, the slake lime has to harden first, then it has to get mixed with soil (Jamal 2017). In the review conducted by Hamard et al. (2016), it is mentioned that lime is sometimes added to adobe's mixture as a stabilizer. Adobe and cob mixtures are made from similar materials, but with different method of construction. While cob is considered a stacked earthen construction method, adobe is a form of earthen construction that uses molded earth block. In another study conducted on adobe to analyze the stability of lime-clayey bricks (Chen 2009), it is determined that when 10% or less of lime is introduced into the mixture of adobe bricks, the compressive and bending strengths increase and water absorption decreases. Furthermore, in the study performed by Millogo et al. (2012), lime was added to lateritic soils to strengthen their properties. Millogo et al. (2012) mention that lateritic and clayey soils would have similar performance after the addition of lime. The study concluded that the optimal compressive and tensile strengths were reached with the addition of 3% of lime by weight (Millogo et al. 2012). Figure 2 shows Millogo et al. (2012) test results, which illustrate the compressive and tensile strength obtained with the corresponding lime content for its weight percentage. The data presented in Figure 2 indicates that including 2%–4% of lime in the mixture would result in having the optimum strength. Such results would guide development of mixture designs for 3D printing of cob.

2.2 Traditional Cob Construction Process

The first step in developing any mixture design is to determine the proportions of the ingredients. For a typical cob construction, the literature review by Gomaa et al. (2019) and Hamard et al. (2016) has shown that for the best performance, the cob mixture should consist of 78% subsoil, of which clay would be around 20% and sand 80%. The rest of the mixture should consist of 2% straw and 20% water. After determining the amount of materials, the dry materials are poured on a tarp placed on a leveled surface, as shown in Figure 3-A. This is followed by adding water to the mixture, as shown in Figure 3-B. The mixture is then mixed by stepping on it, as shown in Figure 3-C until the mixture starts to look homogenous. The next step is to grab one of the tarp corners and fold it on the mixture to get a rolled mixture (Figure 3-D), followed by another round of stepping on it to ensure all materials are well mixed. Finally, straws are added on top of the mixture, and the mixing process repeated until the mixture becomes homogenous.

After preparing a homogenous mixture, the workers divide the mixture into small rounded lumps, which do not have to be of the same size, nor do they have to be perfectly round, as shown in Figure 3-E. The final step in cob construction is to build the wall, which starts by dropping the round lumps into the wall's base. Usually, the wall has a masonry plinth as the base to build on it. At this step, it is imperative to build the first layer as quickly as possible to ensure that the mixture does not dry out. After establishing the first layer and ensuring it is level, holes are created in the layer by workers pressing their thumbs against it, as shown in Figure 3-F. These holes allow the second layer to key into it, which in return would create a monolithic structure.

It is clear that being highly labor-intensive, traditional cob construction is not currently of great interest where labor costs will be prohibitive. However, today's technology can offer a modern approach to cob construction with minimal labor. One such approach is 3D printing of cob, which would employ gantry frame of industrial robotic arm for the construction, thus significantly cutting down on the labor need and construction time. Alhumayani et al. (2020) compared the environmental impact of traditional cob, conventional concrete, 3DP cob, and 3DP concrete. The results show that traditional cob had the least overall environmental impact. The study indicates that 3DP cob has an environmental impact that is higher than traditional cob, but needless to say, much less than the conventional and 3DP concrete impact (due to the use of Portland cement), and this can be considered a motivation to use 3DP cob instead of 3DP concrete.

3. TRANSITIONING TO 3D PRINTING

As modern building construction shifted away from traditional construction, and concrete replaced earth materials as the preferred conventional practice, the building industry became responsible for almost one-third of the total greenhouse gas emissions (Arooz & Halwatura 2017, Craveiro et al. 2018, Ürge-Vorsatz et al. 2012). Based on the results of the work by Morton (2008), Illamps et al. (2009) and Riza et al. (2011) state that studies have shown that a typical concrete masonry block emission is estimated as 143 kg of carbon dioxide (CO_2)/metric ton of concrete blocks. In contrast, the CO_2 emission of a conventional earth brick masonry is approximately 22kg of CO_2/metric ton of earth bricks (Illampas et al. 2009, Riza et al. 2011). This shows that using earth-based materials for buildings would enhance the overall building industry's sustainability efforts. Using earth-based materials would result in a more

FIGURE 3. The traditional cob construction process.

Placing dry cob materials on the tarp (Courtesy of McIntosh 2014)

Adding water to the mixture (Courtesy of McIntosh 2014)

Mixing cob by foot (Courtesy of McIntosh 2014)

D. Folding tarp to ensure a homogeneous mixture (Courtesy of Boddington 2020)

E. Stacking lumped cob specimens (Courtesy of McIntosh 2014)

F. Cob structure during construction (Courtesy of Boddington 2020)

environmentally friendly building industry by providing a locally sourced, biodegradable material with low greenhouse gas emissions (Illampas et al. 2009).

The above literature review also shows that the amount of construction material used is proportional to the amount of CO_2 emission. Therefore, consuming less material would result in less CO_2 emission. Traditional load-bearing construction involves using heavy and solid elements such as beams, columns, walls, and floors. Often the use of materials such as concrete in making these structural components is not an optimized practice, as the material is being used in areas of the components where it might not be needed to resist the applied loads. Using excess material is a waste and would result in excess greenhouse gas emissions. Furthermore, Alhumayani et al. (2020) studied the environmental impact of four walls that were constructed differently. The study used a standard Life Cycle Assessment (LCA) to assess the environmental impact of the walls. The walls' environmental impact were based on global warming, ozone depletion, fine particulate matter, marine eutrophication, land use, mineral resource scarcity, and Available Water Remaining (AWARE). The authors (Alhumayani et al. 2020) included a traditional cob wall as a "base line" since their hypothesis indicated that this wall would be the most environmentally friendly. However, the results shown in Table 1 indicate that the 3DP cob wall and the 3DP concrete wall had a lower environmental impact in marine eutrophication, land use, and mineral resource scarcity than the traditional cob wall. The 3DP cob wall effect on ozone depletion and AWARE was also better then the traditional cob.

TABLE 1. Environmental Effect of Different Types of Walls (adapted from Alhumayani et al. (2020).

	3DP Cob	Traditional Cob	3DP Concrete	Conventional Concrete
Thickness	0.5	0.6	0.4	N.A.
Type	Not solid	Solid	Not solid	Solid
Volume (m^3)	0.31	0.6	0.16	0.3
Global warming	8%	1.8%	100%	73%
Ozone depletion	68%	70%	89%	100%
Fine particulate matter	14%	2%	76%	100%
Marine eutrophication	66%	100%	39%	74%
Land use	17%	26%	6%	100%
Mineral resource scarcity	60%	100%	32%	82%
AWARE	50%	66%	85%	100%

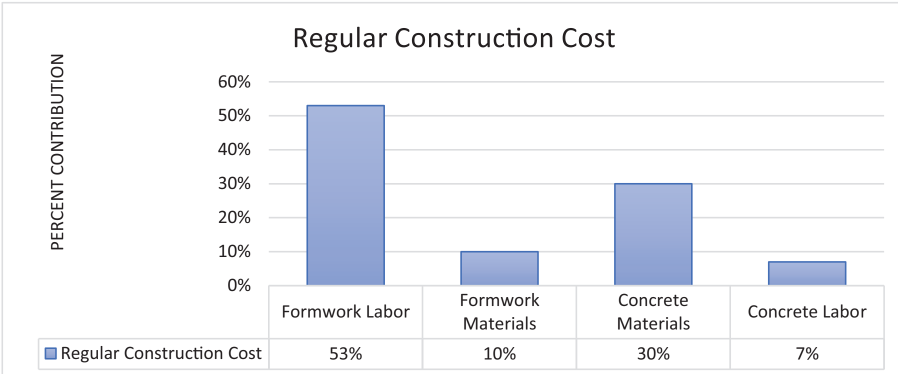
3.1 3DP of Concrete

One solution to optimize concrete material usage is through 3D Printing of Concrete (3DPC), as opposed to cast in place. In 3DP, or sometimes known as additive manufacturing (AM) or additive construction (AC), the dry concrete materials including cement, fine and coarse aggregates, and admixtures are mixed in a mixer with water and then pumped through a hose and a nozzle, which extrudes the material as a filament into the designated location by the use of a robot arm or gantry frame system. Consecutive layers of extruded concrete are needed to construct an architectural or structural element. Since the concrete filament is deposited only in designated locations, the elements printed no longer must have a solid interior design (Ko et al. 2018), e.g., the web of a beam need not be solid and can have opening where shear stress is low, thus minimizing the use of material while satisfying structural capacity requirements. Therefore, the application of 3DP in construction would reduce material usage and result in a lower greenhouse gas emission.

One major economical advantage of using 3DPC is that it requires no formwork (Paul et al. 2017), which gives flexibility in design. Figure 4 shows the percent contribution of the total construction cost for formwork labor and material as well as that of concrete labor and material for a conventional construction (Paul, et al. 2017, Jha, 2012). This chart shows that in regular concrete construction, formwork by itself contributes to more than 50% of the cost. Therefore, by shifting the construction from typical construction to 3DP, the construction cost reduces more than 50%.

Moreover, the printed concrete's geometry plays an essential role in the building's strength to resist structural loads. Since the 3DPC structure is printed without the use of formwork, the concrete needs to support its weight and the weight of the layers deposited on top of it. Accordingly, geometric nonlinearity might result in instability of a layer, which in return would cause a collapse in successive layers (Bester et al. 2019). According to Kashani and Ngo (2018), to have a successfully printed structure, the concrete's uncured properties need to be sufficient

FIGURE 4. Regular Construction Cost Contribution Chart. (Adapted from Paul, et al. 2017 in reference to Jha 2012).



to encounter the flowability of the system and the buildability to withstand the material's self-weight and the weight of the successive layers.

3.2 3DP of earth-based materials

The above literature review shows that buildings constructed using traditional cob technique were made of mud without reinforcement. 3DP of clay-based mixtures can benefit from such traditional construction experience as it would be printing clay without formwork and reinforcement. Therefore, learning about the mixture design and shapes of traditional earthen material and unreinforced buildings will help in generating a modern 3D printed version. Furthermore, as Alhumayani et al. (2020) study of the environmental effect of four different walls has shown, the 3D printed cob wall can reduce the overall environmental impact by 85% compared to the conventional concrete wall and 80% compared to the 3D printed concrete wall. Therefore, it can be concluded that 3D printing of earth-based material would result in a sustainable building material with lower CO_2 emission. However, there is a need to determine the potential of having a printable local clay-based concrete mixture and identify the shortcomings of the ongoing research and development in this field. Accordingly, mixtures used in different studies are subsequently evaluated for their printability, buildability, and strength. The limited available 3DP clay mixtures found in the literature are based on the experience of mixtures used in historical clay buildings also found in the literature. However, the mixture is altered to provide appropriate printability and buildability properties, while maintaining the mixture's strength. Furthermore, the literature reviewed also provides the economical and environmental benefits of having a printed mud-based concrete using local soil.

To support the goal of this study in exploring environmentally friendly building materials, a clay-based mixture is considered to be used instead of concrete. Since in 3DP, the fresh properties of the material play an important role in determining the success of the printed structure (Kashani and Ngo 2018), the fresh properties of the clay-based material need to be analyzed to achieve a printable mixture that would lead to print a stable structure. 3DP of clay-based material will result in establishing an optimum material usage of an environmentally friendly material, i.e., a material with low CO_2 emissions. However, one of the challenges faced is that clay-based mixtures are usually worked with in a plastic state, which results in insufficient fresh properties such as buildability to allow the material to remain stable under its own weight

(Hamard et al. 2016). To overcome this challenge in a typical traditional cob construction, walls are built by placing monolithic portions of cob successively. These portions are called lifts (Hamard et al. 2016). A new lift does not get to be placed until the preceding lift has gained enough strength to support the weight of the new lift (Hamard et al. 2016). On the other hand, during the 3DP process, layers (much thinner compared to cob layers) are to be printed on top of one another, with not much time to cure. This disadvantage can be manipulated by designing the printed structure's toolpath as well as the mixture design in such a way that it will provide some time for the printed layer to cure before the next layer gets deposited, which in return would increase the layer's buildability. The toolpath, or sometimes known as the printing path, is the trail the robot arm takes while extruding the material. The material's buildability can also be governed by the addition of admixtures, which would adjust the setting time of the printed layer. In addition to the printed material's fresh properties, other factors that help in establishing a stable structure include the printing parameters such as the shape of the nozzle, the extrusion rate, and the time it takes to print the structure (Kashani and Ngo 2018).

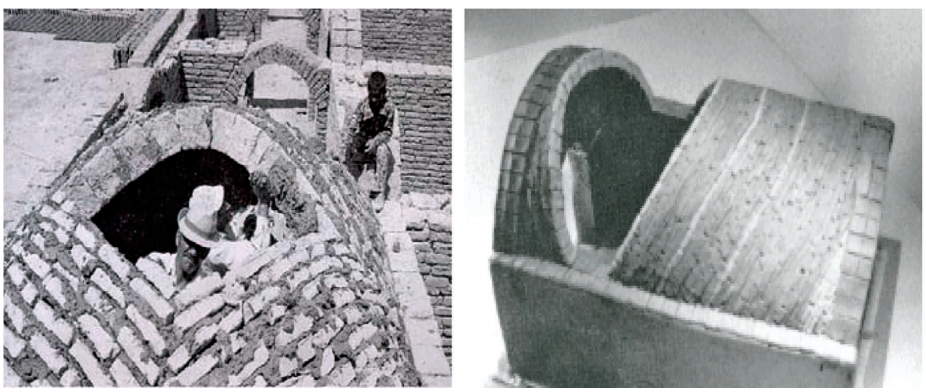
Furthermore, knowing the strengths and weaknesses of the material used can also help in establishing a stable structure using optimum shape for an unreinforced brittle material. For example, clay-based materials are considered to have a low tensile capacity. Therefore, to be able to 3D print a stable cob structure and to prevent collapse, the 3D printed structure should be able to resist loads mostly in compression. A dome structure is one example of a structure resisting its loads mostly through compression. According to Saliklis (2008), a well-designed dome structure will withstand loads mainly through compression. This explains why most traditional and historical clay-based structures tend to have a dome-like or cone shape. One example of such structures is the Syrian Beehive Houses shown in Figure 5-A, where the houses have been made of thick mud-brick walls designed in a high domed shape. Khoshnevis (2004) mentions that the ancient method of constructing a dome structure using clay-based material, as shown in Figure 5-B, could be used in 3DP to build a supportless structure. Therefore, to provide a stable clay-based 3DP structure, a 3D printed cob house structure design should be able to withstand the applied loads mainly through compressive stresses.

To develop a printable clay-based mixture, a thorough literature review on different clay-based mixtures was done. Most of the current literature focuses on testing a historical clay-based building's durability or retrofitting an old clay-based building (Illampas et al. 2009; Hamiane et al. 2016). Some other studies have focussed on establishing an enhanced clay-based material by adding different additives like seaweed biopolymers (Perrot et al. 2018; Dove et al. 2016) or by introducing new materials to the mixture like crushed seashells (Soneye et al. 2016).

Since cob is usually made with local materials, its material properties differ with different subsoils. For this reason, as different soils are used for cob, different proportions of clay, sand, and water are used in each cob mixture. However, most of these proportions are close to each other, which indicates that for each material, there is an optimal range for intended usage. On the other hand, to be able to print the mixture, it needs to be able to flow through a hose into a nozzle. Gomaa et al. (2019) tried to print a cob material with typical proportions. Due to the low amount of water present in the mixture, excessive friction force was generated in the extrusion circuit, and therefore the mixture was not able to be printed. Therefore, an increase in the mixture's water content is needed to get the mixture to flow. However, an increase in the mixture's water content would result in a) a weaker mixture, b) an increased drying time and shrinkage, c) reduced printed layer stability, and d) reduced layer height (Gomaa et al. 2019, Reyes et al. 2018). Having a printable mixture depends on the ability of the mixture to flow

FIGURE 5-A. Ancient style homes: Syrian beehive houses. (Courtesy of Upyernoz (2005).

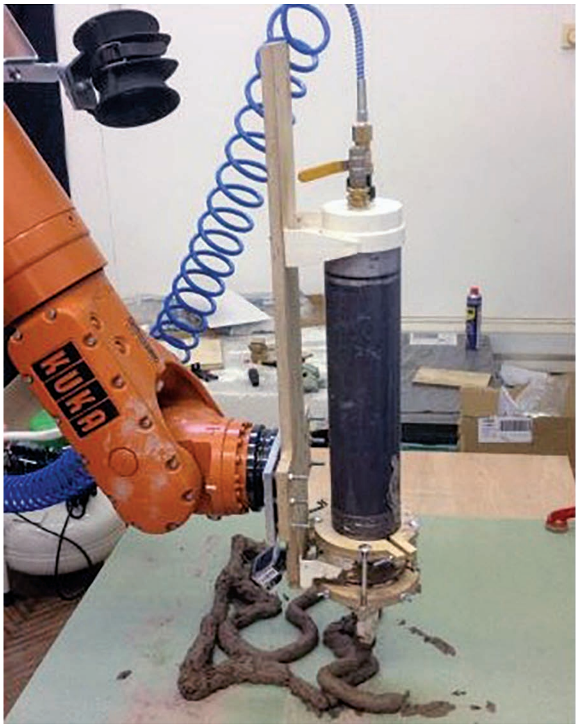
FIGURE 5-B. Ancient style homes: brick dome structure (Courtesy of Khalili 2000).



smoothly within the hose and the extrusion system, to remain stable after printing, and to be able to support the weight of successive layers. Therefore, other materials must be added to the mixture to enhance the rate of the water absorbed by the mixture. According to Chen (2009), to enhance compressive and bending strengths and decrease water absorption of adobe, hydrated lime needs to be added. To accommodate for these benefits within an optimum range, lime should be added to the mixture while reducing other materials' percentages.

Mixtures with different water content need to be tested for their flowability and buildability. Gomaa et al. (2019) tried printing several different mixtures, each with different material proportions. The established new 3DP cob mixture had 25% water, 73% subsoil, and 2% straw (Gomaa et al. 2019). On the other hand, Reyes et al. (2018) achieved a printable mixture by using 30% subsoil, 15% fine silica sand, with 18% water, 15% straw, and 22% clay. This mixture was used to print a scaled model utilizing an air pressure system, which consisted of a manually controlled air compressor with a tube connected to extrude the mixture, as shown in Figure 6 (Reyes et al. 2018). The authors state that printing cob with this system created many

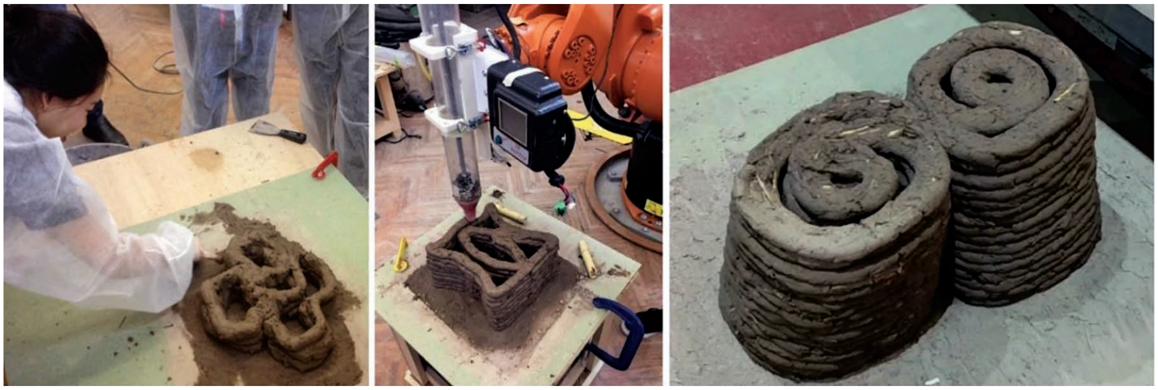
FIGURE 6. Manually controlled compressor used to 3DP cob (Courtesy of Reyes et al. 2018).



challenges in maintaining the uniformity of the printed cob, and in "controlling the speed" of the extrusion. It is also mentioned that the printed cob had some air gaps in it, which prevented the printability of successive layers (Reyes et al. 2018). Therefore, the printing system was changed from an air pressure extrusion system to a mechanical extrusion system, which showed remarkable results in terms of uniformity and quality of the printed cob (Reyes et al. 2018). Figure 7 shows how the printed structure can be affected by the type of extrusion system and different material percentages. The manually controlled air compressor used by Reyes et al. (2018) (shown in Figure 6) was used to print the cob structure on the left side of Figure 7, while the structure shown on the right side of Figure 7 was printed using a mechanical extrusion system. However, Reyes et al. (2018) mention that even though the results achieved using the mechanical system were acceptable, using this system for printing an actual model would still have challenges due to the scale.

According to Paul et al. (2017), the material's rheology that depends on its homogeneity plays an important role in printing a well-designed structure. For this application, rheology helps to examine the material's reaction when exposed to shear stress, which is determined by the way the material flows and deforms (Sali 2016). This could be the cause of the challenges created in the manually controlled air compressor technique reported by Reyes et al. (2018). Therefore, to establish a printable cob material for real size structures, two critical factors need to be taken into account. First, the type of printing system used should be able to mix, pump, and extrude a dense material at a constant rate. Second, the material needs to be well mixed to achieve the required rheological properties. According to Piani et al. (2020), a high fiber content in the mixture tends to increase the mixture's inhomogeneity and voids in some adobe mixtures.

FIGURE 7. The effect of different extrusion systems and different mixtures on the printed cob structure (Courtesy of Reyes et al. 2018).



The authors further explain that the addition of fibers weakens the bond between the material in the mixture, which results in some weak spots. Referencing Illampas et al. (2011), Piani et al. (2020) further explain that adding fibers in the soil mixture can increase porosity in the mixture, which in return would increase the mixture's heterogeneity. For this reason, Hamard et al. (2016) emphasized the need to have evenly distributed water, straw, and clay particles in the mixture to enhance the mixture's mechanical strength.

4. MECHANICAL PROPERTIES OF COB

4.1 Cast Cob Strength

In regular cast-in-place concrete construction, the concrete mixtures are cast as cylinders or short beams and tested to characterize their mechanical properties such as compressive strength and modulus of rupture, from which one can determine the capacity of structural members made of that material. Much like other construction material, the two most important strength factors for cob buildings are the compressive and flexural strengths. The test commonly used to determine the mixture's compressive strength is the cube test (rather than cylinder), while the flexural strength is mostly determined by the mixture's modulus of rupture, which is usually determined based on the third point loading test. The mixture's compressive strength will determine its resistance to gravity loads, while the flexural strength will determine its resistance to cracking due to tensile stresses resulting from the flexural response (e.g., bending due to gravity loads or lateral loading). According to Pullen et al. (2011), since the modulus of rupture measures the tensile stress at which failure occurs, it is an important factor to determine a wall's ability to resist lateral forces. Therefore, determining the mixture's modulus of rupture is crucial in estimating the final printed structure's lateral resisting strength. Furthermore, based on a study conducted to determine the mechanical properties of clay-based masonry, Illampas et al. (2011) reported that the test performed to determine the specimens' flexural strength also revealed the existence of any non-homogeneity in the specimen tested. That was established when the mode of failure of nonhomogeneous specimens occurred near the material discontinuity, such as the presence of pebbles or cracks (Illampas, et al. 2011). On the other hand, failure along the beam at the point of loading only existed in homogenous specimens (Illampas, et al. 2011). Therefore, reporting the mode of failure for different mixtures will provide evidence for the mixture's homogeneity.

4.2 Strength of 3D Printed Cob

In 3DP structures, the mixture used may prove to be printable and buildable; however, it still needs to be tested for its strength. In the research conducted by Paul et al. (2017), it was concluded that the mechanical properties of 3DP materials are dependent on the design of the printed structure, the direction of the printed layer, and the shape of the nozzle opening. Paul et al. (2017) presented three different ways to apply the load on the printed specimens concerning the printed layer's direction. Figure 8-1 shows the three methods of applying a load to the specimen to get the specimen's compressive strength, while Figure 8-2 shows the three ways of applying a load to the specimen to get the specimen's flexural strength. Depending on the applied load relation with the printed layer's direction, the test results were either higher or lower than the cast specimen's strength. However, according to Paul et al. (2017) in reference to Feng et al. (2015), in other tests, the printed specimen's compressive strength was higher when the load was applied parallel to the layer direction compared to the case when the load was applied perpendicular to the layer direction. Paul et al. (2017) also mention that when the load is applied in the X direction (Figure 8), the 3DP specimens' weak joints might split, and as a result, the strength obtained by applying the load in this direction was the lowest strength recorded in both tests. When the load is applied in the Z direction, the strength of the specimen

FIGURE 1-1. Three ways of applying load with respect to the layer direction to get the specimen's compressive strength (Adapted from Paul, et al. 2017).

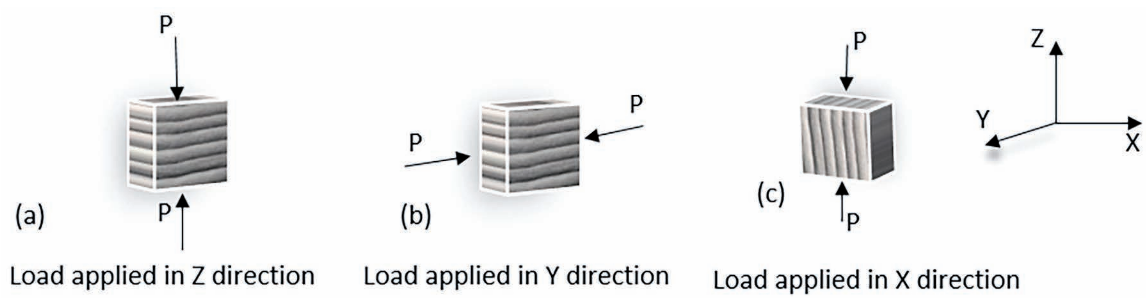
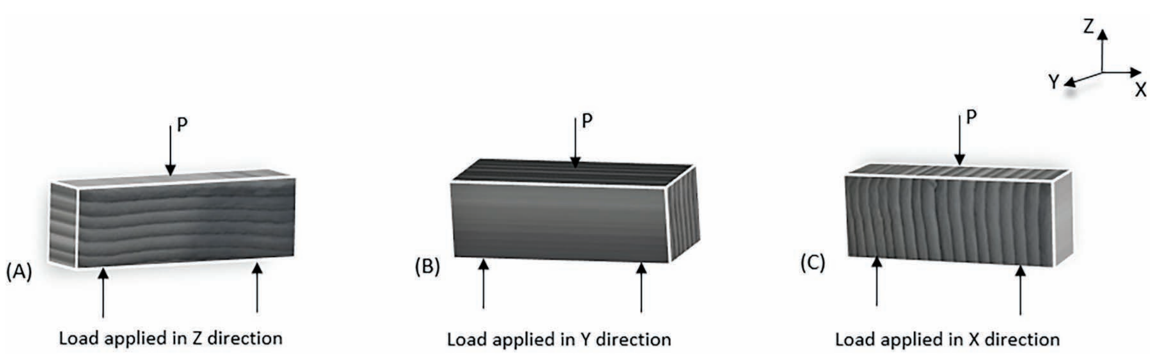


FIGURE 1-2. Three ways of applying the load with respect to the layer direction to get the specimen's flexural strength (Adapted from Paul, et al. 2017).



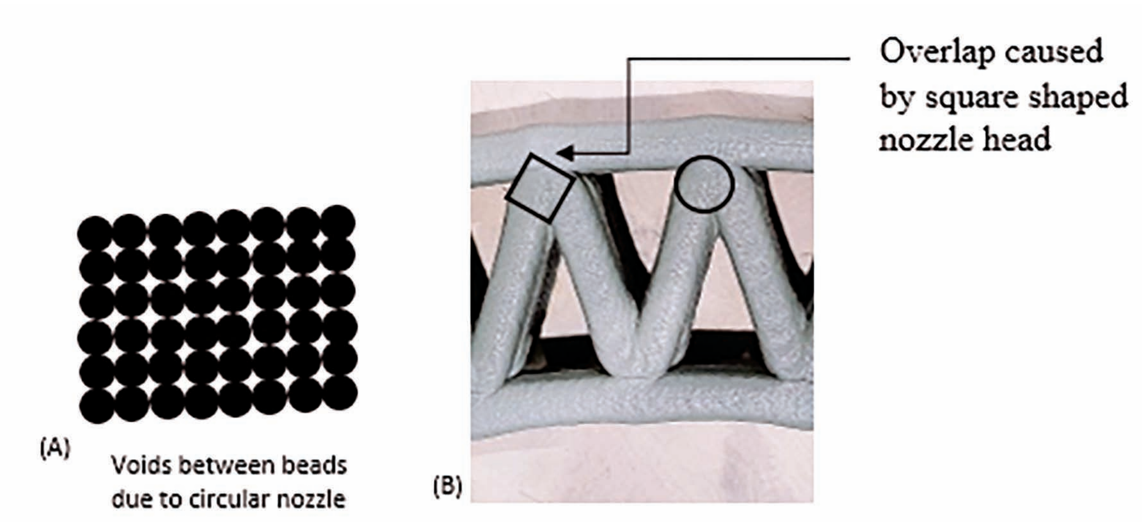
is dependent on the bond between the layers (Paul et al. 2017). The extent and effectiveness of contact between the layers, the time elapsed between two successive layers (the open time), and the material properties are some factors that affect the strength of the bond between layers (Paul et al. 2017). The shape of the nozzle opening also contributes to the strength of the bond between layers.

4.2.1 Effect of Different Nozzle Heads on 3DP Cob Strength

As stated in section 4.2., the 3DP specimens' strength is a function of the layers' bond property, which depends on the shape of the layer and the amount of contact surface with other layers. The shape of the nozzle head (e.g., square or circular) plays an important role in determining the printed layer's shape and the amount of contact surface. Figure 9 shows some disadvantages of circular and square nozzle heads (Paul et al. 2017). For example, Figure 9 (A) shows that the circular nozzle head tends to create voids in the printed structure; having voids reduces the contact surface, which in return reduces the strength of the structure (Paul et al. 2017). However, the circular nozzle head allows the deposited material to remain symmetrical, even if it was printed at an angle (Paul et al. 2017). Therefore, using a circular nozzle is better for printing structures with complex designs (Paul et al. 2017). Figure 9 (B) shows the path of the deposited layer for square and circular nozzle head shape. The layer deposited by the square nozzle tends to exceed the specified path of the layer due to the shape of the nozzle head, whereas the layer deposited by the circular nozzle falls within the specified path of the layer (Paul et al. 2017).

All these factors play an important role in determining the quality and strength of the final printed structure. For example, according to Figure 8-1 (A) and 8-2 (A), for the test performed with the load applied in the Z direction, the resulting strength depends on the amount of contact provided between the layers, with rectangular nozzle creating more contact surface and thus a higher strength than a circular nozzle (Paul et al. 2017). Therefore, to get the most accurate results, the type of nozzle used to print the final structure should be the same as the type of nozzle used to print the elements used for testing. Furthermore, the final design of the structure should be based on a path that can be traveled by the chosen nozzle.

FIGURE 9. Disadvantages of circular and square nozzle. (Adapted from Paul, et al. 2017).



4.2.2 Compressive and Flexural Tests Results

Based on the results of the work done by Norton (1997) and Morel and Pkla (2002), Illampas et al. (2011) report that a cast clay-based specimen's flexural strength falls somewhere between 10% to 20% of its compressive strength. However, Illampas et al. (2011) results did not show any connection between the flexural and compressive strengths of the specimens. The authors (Illampas et al. 2011) attribute variation of their flexural test results to the unpredictability of local clay-based specimens. For this reason, Fordice (2017) expressed the need for a unified test that considers all factors that could affect the strength of cob construction. For example, the type of soil used, its plasticity, its liquid limit, and the size and shape of its particles all play an important role in the mixture's strength (Fordice 2017). The type of straw used, its length, its orientation, and its proportion also contribute to the mixture's strength result (Fordice 2017). Accordingly, Fordice (2017) states that "standard ASTM tests are not designed for cob." To appropriately include the effect of straw in a typical cob wall, Cob Research Institute (CRI) suggests testing a 12 inches cube to account for the typical wall width and therefore capture the actual effect of straw in a cob wall (Fordice 2017). On the other hand, Gunawardena (2008) mentions that a typical cob wall thickness ranges from 450mm (17.7 in.) to 600mm (23.6 in.). This confirms the vernacular identity of cob and reinforces the need for a uniform standard. Illampas et al. (2014) also confirm that there is no specific formal test to determine the compressive strength of a clay-based material. While there are some ground rules on testing clay based bricks, there is still no consensus, and therefore, testing clay-based elements for their compressive strength usually follows the procedure of other masonry units (Illampas et al. 2014).

While the authors of this paper recognize the need for quantitative analysis that compares several traditional cob mixtures' mechanical strength with respect to several 3D printed cob mixtures, the current literature lacks such information. To the authors' knowledge, the information found in the literature on 3D printed clay-based mixture is very limited, which is mostly due to the fact that the current efforts on 3D printed earth-based mixtures are done in the construction industries with not much information shared in the open literature. As one of the very few published works, Perrot et al. (2018) report in Table 2 the properties of their 3D printed earth-based materials for compression strength with and without alginate. For comparison purposes, Table 2 also shows test results by Fordice et al. (2017) that compare several traditional cob mixtures' compressive and flexural strengths. Due to the lack of information on the flexural strength of 3D printed earth-based mixtures in the current literature, no comparison between typical cob mixture and 3D printed cob's flexural strength has been provided.

4.2.3 Compressive Strength Tests Based on ASTM Standard

Illampas et al. (2014) mention that the most widely used testing procedure is the "direct load testing of specimens." According to ASTM-C109, the mixture needs to be divided into small cubes of 50mm (2 in.), as shown in Figure 10. A loading rate of 200 to 400 lb/s is to be applied to the cube's surface that was in contact with the mold (ASTM-C109). The maximum load reached is then divided by the area of the loaded surface to determine the specimen's compressive strength (ASTM-C109). Paul et al. (2017) tested the specimen's strength on the 7th, 14th, and 28th days after the specimen was printed or cast. On the other hand, Illampas et al. (2017) specimens were mixed and left in a closed plastic box for three days before the cast day to allow moisture to be equally absorbed by the materials. The specimens were then placed in a ventilated oven at 70°C for two days and then tested on the 42 ± 2 days after the cast day (Illampas et al. 2017).

TABLE 2. Comparison Between Traditional Cob and 3DP Cob Compressive Strength.

Traditional Cob Mixtures				3D Printed Earth-Based Mixture			
Type of mixture	Test Method	Average Compre-ssion Strength (psi)	Reference	Type of printed specimen	Test Method	Average Compression Strength (MPa)	Reference
Long straw	Standard 4” × 8” Concrete Cylinders Test	41	Rizza and Böttger (2013)	Circular nozzle with alginate		1.21±0.03	Perrot et al. (2018)
Chopped straw	Standard 4" × 8" Concrete Cylinders Test	76	Rizza and Böttger (2013)	Circulat nozzle without alginate		1.22±0.04	Perrot et al. (2018)
	Using 38 mm diameter compression disc (unspecified standards)	87	Akinkurolere et al. (2006)	Rectangular nozzle with alginate		1.77±0.03	Perrot et al. (2018)
Conventional	Standard 4" × 8" Concrete Cylinders Test	88	Rizza and Böttger (2013)	Rectangular nozzle without alginate		1.65±0.04	Perrot et al. (2018)
	ASTM C39	102	Pullen and Scholz (2011)				

The ASTM-C109 test could be performed on cast cubes as well as printed cubes. To consolidate the mixture, the cast cubes are to be compacted by manually tamping the specimen; if needed, a vibrating table could be used to help compact the specimens into the molds. On the other hand, the printed cubes are to be withdrawn from a larger printed element after enough time to solidify but not to reach its ultimate strength. For example, Paul et al. (2017) withdrew the printed test cubes from the larger printed elements on the 3rd day. Furthermore, ASTM requires the load to be applied to the surface that was in contact with the mold. Since this does not apply to the printed element case, one surface of the cube could be smoothed before applying the load to it.

4.2.4 Flexural Strength Test

Two tests could be done to determine the mixture's modulus of rupture, the splitting cylinder test, and the third point loading test. Matthys and Grimm (1979) used a third-point (sometimes called four point) loading test based on ASTM E518 standards to establish the modulus of rupture of nonreinforced brick masonry using the following equation:

$$R = \frac{\left(P + 0.75P_s\right)L}{bd^2}$$

FIGURE 10. Cob cubes to be tested.

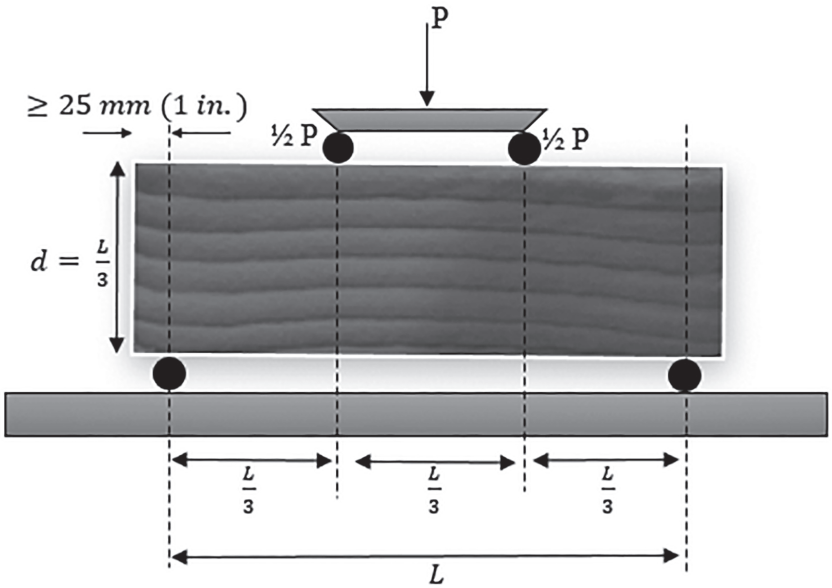
where R is the gross area modulus of rupture, P is the load recorded at failure in addition to the channel weight, P_s is the specimen weight, L is the span, b is the average specimen width, and d is the average specimen depth. A third-point loading test, as defined by ASTM C-78, requires the element to be simply supported and the load to be applied to the element at two different points (one-third span apart), as shown in Figure 11. This test could be performed on cast beams as well as printed beams. Matthys and Grimm (1979) tested their specimens every day from the first day until the seventh, and on the 14th, 21st, and 28th. On the other hand, Illampas et al. (2017) used a three-point bending test, which requires a single load at mid-span of a simply-supported beam. Paul et al. (2017) also used a three-point bending based on the British Standard (BS EN 196-1:2016). As discussed earlier, the printed cube or beam test results are dependent on the relation between the applied load and the direction of the printed layers. To account for the different strengths, 9 cubes or beams (3 in each axis) from the same mixture could be printed, and the load can be applied along different axes. To be precise with the cast cubes, the extracted 3D printed cubes should have similar dimensions as the cast cubes, i.e., 50mm (2 in.). However, for the flexural test, ASTM C78 does not specify a specific beam dimension. The beam's supports should be at a distance equals to three times its depth, as shown in Figure 11, and the supports should be at least 25mm (1 in.) away from the edge of the beam. Moreover, the load supports should be at a distance equal to the beam's depth. The beam's setup as specified by ASTM C78 is shown in Figure 11. The results of the printed cubes/beams can then be averaged and compared to the cast cube/beam.

5. RECENT CONSTRUCTION OF COB STRUCTURES

5.1 Traditional Cob Construction

Figure 12 shows one example of the traditional cob cottages that are typically found in Devon, Wiltshire, and Hampshire, England, and its tag plate indicates that the building was built in 1539 (Cob Cottage Company). Even though cob is considered a vernacular construction, it has proven its soundness and reliability for home and other building construction over time, as evidenced in historical buildings that remain today. In the current time, the lack of specific

FIGURE 11. Third-point Loading Test setup. (Adapted from ASTM C78).



code that takes into account all factors that could affect it is preventing cob construction from being used (Fordice 2017). In the research done by Fordice (2017) on building with cob in North America, it was concluded that there are only three legal ways to build with cob. The first way to get by with building a structure with cob is to build a small structure of 120 ft^2 area. However, Fordice (2017) suggests the structure still needs to be built with respect to code specifications (e.g., International Building Code) but should not be considered a habitable structure. Cob structures could also be built with the "Owner-Builder Code" in designated locations. Owner-Builder Code is a less restricted code that limits the use of the structure

FIGURE 12. Historical cob building found in Devon, England (Courtesy of Cob cottage in reference to Evans, 2020).

and is permitted in only some rural areas (Fordice 2017). Lastly, cob structures could be built under the alternative materials and methods (AMM) section found in the IBC. According to Fordice (2017) in reference to Dente (2017), in an approach to construct a cob building under AMM section specifications, the material properties based on available test results are used. Accordingly, field testing is also necessary to verify that the actual material's test results are close to the test results from other sources (Fordice 2017) and a factor of safety also needs to be added. Having only these two processes to legally build a habitat with cob has resulted in increased cob construction expenses (Fordice 2017). Accordingly, in some agricultural areas cob has been built illegally (Fordice 2017), which when recognized by the County Building Department, the owner was required to obtain a "post-construction permit" by retrofitting the structure until the structural specifications were met (Fordice 2017) in reference to (Pullen et al. 2011). However, a recent development is that the CRI's cob code has been approved to be included in the 2021 International Residential Code (IRC) in the U.S. and other countries (CRI 2020). Having a code specifically for cob construction will not only ease cob construction but will also provide better guidelines to retrofit historical cob structures.

5.2 3DP of Earth-Based Mixtures in Construction

While the efforts discussed on 3DP of cob are all research-based, some actual construction efforts are also focused on 3DP using earth-based mixtures. In 2018, a company called World's Advanced Saving Project (WASP) was able to establish the first 3DP house with a mixture made of natural materials found near the construction area (Chiusoli 2018). The 3D printed house mixture consisted of 40% "straw chopped rice, 25% rice husk," 25% of on-site soil, which contained 40% silt, 30% sand, and 30% clay, and 10% of lime (Chiusoli 2018). The company mentions that having a mixer that is able to mix the material until a homogeneous mixture in workable conditions is achieved, aided in 3D printing the structure, with the wall having "almost zero environmental impact" (Chiusoli 2018). Furthermore, as Figure 13 shows the interior of the 3D printed wall (Chiusoli 2018), it does not have a solid element. The final structure, however, is not a fully 3D printed structure; it consists of 3D printed walls with windows and a timber roof. The 3D printed walls provide evidence that 3D printed elements no longer have to maintain a solid geometry and that it can have complex section geometry that cannot be constructed using typical construction using formwork (Chiusoli 2018). The walls also prove that 3DP of earth-based material can provide an environmentally friendly structure. The structure was 3D printed on a cementitious foundation; the role of this foundation is similar to the masonry plinth used as the base in historical cob construction. The base not only provides a leveled surface for the structure to be built on, it also acts as a barrier to prevent water from getting into the cob structure through capillary action (Sumerall 2020).

On the other hand, WASP is currently in the process of building a village that consists of fully 3D printed houses using a material mixture that will use local clay (Chiusoli 2019). According to Chiusoli (2019), the goal of this village is to provide fast construction sustainable affordable housing with no waste, as the mixture is biodegradable. The planned 3DP houses would be constructed in a dome-shaped structure, a geometry established by tests to develop a self-supported structure. This supports the hypothesis expressed by Khoshnevis (2004) that we can 3D print a structurally stable clay house if the shape is dome-like.

Another attempt in 3DP earth-based material was done by the Institute for Advanced Architecture of Catalonia (IAAC 2020), which 3D printed a 5 meters high and 2 meters wide wall using a local-based adobe mixture (IAAC 2020). The thickness of the wall varies vertically,

FIGURE 13. Gaia, the first 3DP structure made from earth, walls interior section view (Courtesy of Chiusoli 2018)

with 0.7 meters at the bottom and 0.2 meters at the top (IAAC 2020). The self-supported wall is considered load-bearing with a wooden slab connected to it at 2.6 meters high to test the load transfer from the slab to the wall (IAAC 2020). Accordingly, the load transferred from the slab was taken into account in the design of the wall along with the wall's self-weight (IAAC 2020). The wall's interior design looks similar to the WASP wall, i.e., it has open cell cross-section. The IAAC wall was printed using recycled materials that were used in previous prints, which reduces the environmental impacts significantly (IAAC 2020). IAAC also mentions that the use of a robot made the structural elements customized to meet the specified structural requirements. In a combined effort, WASP and IAAC 3D printed a 40 cm (15.75 inches) thick load-bearing wall made of earth-based materials (Chiusoli 2019). The wall was designed with designated hollow spaces (cores or cells), which are then used to interconnect wood elements to support stairs allowing the stairs to be integrated into the wall (Chiusoli 2019) as shown in Figure 14. Furthermore, a team from Emerging Objects 3D printed four different structures from local earth-based materials. Their first project is called "Hearth," which is reinforced with wood that is visible from the exterior. The structure also includes a 3D printed bench that is attached to the interior of the walls, and a fireplace located next to the bench (Emerging Objects 2020). The second project called "Beacon" consists of thin walls with some architectural aesthetic touches (Emerging Objects 2020). The third project called the "Lookout" is a spiral stairway, and the fourth one called "Kiln," is a kiln made from 3D printed walls (Emerging Objects 2020). All 3D printed structures by Emerging Objects have open roofs and no slab at the bottom. Having an actual 3D printed structure of earth-based materials shows the industry's interest and readiness for use of such materials. As more projects are currently focused on 3DP load-bearing structures made of earth-based materials, the need to have a code specifically for earth-based materials is essential.

FIGURE 14. 3DP earth-based load bearing wall with embedded stairs (Courtesy of Chiusoli 2019).

6. SUMMARY AND CONCLUSIONS

To sum up, as a historical construction method, cob has proven its soundness and reliability throughout history and potentially as an environmentally friendly material for contemporary construction. Of course, as concrete became the new norm in construction at the beginning of the 20th century, cob construction started to vanish. As a result of the ubiquitous use of concrete, the building construction sector became responsible for almost one-third of the total greenhouse gas emissions. In an attempt to redirect the building industry into a more environmentally friendly manner, there is a growing interest in research communities and the construction industry in a new generation of earth construction. However, without a specific building code recognition, cob construction is not going to be widely accepted by developers, designers, and builders, which means such construction will have relatively high construction costs. Based on the research reviewed, there are three ways to build a cob house legally in North America: a) constructing a small non-residential building that is built to building code specifications, b) to build under owner-builder codes, and c) to build with respect to the Alternative Materials and Methods (AMM) section found in IBC. Based on the literature reviewed, in an attempt to build under the AMM section, field test results need to be compared with strength values obtained from published test reports. This shows that the current construction industry relies on the research community in typical cob construction. The literature review presented shows that cob mixtures are tested based on ASTM standards, which are not specific for cob construction. Therefore, since such ASTM standards have not been developed for cob construction, the resulting tests do not provide consistent and accurate results. Of course, this will not remain the case for too long, as the cob construction appendix submitted by Cob Research Institute (CRI) is approved to be included in the International Residential Code (IRC).

Typical construction process uses materials in an excess manner, which results in unoptimized material usage. On the other hand, the construction of buildings using 3DP can reduce material usage and result in an optimized and customized structure. Using 3DP techniques to print an arrangement with an environmentally friendly material, such as cob or adobe, would result in a less labor-intensive, more environmentally friendly, and highly affordable construction. Only a very limited number of references are available that discuss the potential of using 3DP for cob type construction. The cob mixtures used for 3DP purposes are different from the typical traditional cob mixture, mainly to allow the mixture to be able to get extruded from the nozzle. However, the changes made to the mixture should not affect the mixture's buildability and strength properties, as the success of the printed structures depends on the mixture and extrusion system. Testing a 3DP cob specimen requires the same testing procedures that are required for a cast specimen, but the tests should be repeated three times to take into account the three different axes of the printed layer. The results should then be averaged and compared to the cast specimen test result. While the authors recognize the need for quantitative analysis that compares traditional cob's mechanical strength with respect to different 3D printed cob, the current literature lacks such information. The information found in the literature on 3D printed clay-based mixture is very limited, partly because the current efforts on 3DP earth-based mixtures are done in the construction industries with not much information developed/shared in open literature. Although in 3DP of earth materials, current studies have shown success in establishing 3D printable mixtures, it is also clear that using such mixtures to print a full structure will face some challenges, which requires further studies before commercialization. Nonetheless, the construction industry has shown relative success in overcoming some of the challenges in 3D printing structures with earth-based materials, for both load-bearing and non-load-bearing elements.

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