Chapter 6: Conclusion

This thesis has investigated 3D printing as a method of forming ceramic materials that share both compositional and aesthetic properties associated with an ancient Egyptian self-glazing ceramic known as faience. Archaeologists recognise three types of faience, each made using a different glazing technique. These techniques are known as efflorescence, application and cementation glazing. This PhD project has focused on the development of cementation compositions for 3D printing as well as the development of an efflorescent composition for novel 3D paste extrusion techniques. These compositions were developed and tested using an iterative approach and assessed through the production of physical artefacts. Additionally, a proof of principal study was also conducted to assess the potential for developing a highly vitrified ceramic ware for powder binder 3D printing. Glassy compositions are also historically associated with faience production, however due to certain limitations that were found to be inherent to both the material and the fabrication process, a different single fired ceramic ware was used as a starting point for the glassy ceramic study; Parian ware.

The purpose of this chapter is to review the methods and outcomes of the research and to point to the key findings and contributions it has made to the fields of art, design and 3D printing. Additionally, further opportunities for development within this area of creative technologies will be suggested.

The chapter will begin by reviewing the research question and the aims and objectives identified at the start of the thesis and will identify the extent to which these have been addressed within this study. Once the aims and objectives have been reviewed, this chapter will go on to reflect on the wider achievements of the research and to state what the key contributions to knowledge made by this enquiry have been. The chapter will conclude by pointing to the significant potential for further development of 3D printed self-glazed ceramics. Possible ways to overcome some of the limitations identified in this study will be suggested and potential future applications in art, design and museum studies will also be proposed.

Review of the research question, aims and objectives

This research has focused on the development and testing of new materials and methods for 3D printing ceramic objects with self-glazing properties, based on an ancient Egyptian ceramics ware known as faience. The research was undertaken at the UWE Centre for Fine Print Research, a research centre with a strong interdisciplinary ethos and pragmatic approach within the visual arts, crafts and design. This PhD was supervised by specialists in the field of 3D printing who have academic and professional backgrounds in Fine Art Printmaking, Ceramic Technology and Design.

The research question for the PhD project was as follows: Can 3D printing techniques be used to overcome the forming issues associated with traditional cementation-glazed faience techniques?

The PhD project identified as a starting point the well documented observation that traditional faience is difficult to work with by hand in paste form, primarily due to its lack of plasticity. The PhD research aimed to overcome the difficulties in forming faience by developing new ceramic materials for powder binder 3D printing that possess compositional and aesthetic properties traditionally associated with faience.

Archaeologists have identified three glazing methods which are believed to have been used by the ancient Egyptians to create faience. These are efflorescence glazing, cementation glazing and application glazing. In efflorescence glazing, soluble salts present in the faience paste migrate to the surface of an object as it dries, forming a layer which reacts with the silica in the body to form a glaze when fired. In cementation glazing, a ceramic object is placed in a box (saggar) surrounded by a glazing powder and is then fired. During firing a diffusion process takes place between the silica in the object material and the glazing powder resulting in a glassy outer layer forming on the surface of the object. In application glazing, the ceramic object is coated in a glaze slurry which turns into a glassy outer layer when it is fired. In all of these compositions, the inclusion of metal oxides and other metal compounds can result in a range of brightly coloured glazes being produced.

The focus of this PhD study has been to investigate the cementation glazing technique in combination with powder binder 3D printing. Much less is known about cementation glazing compared to both efflorescence and application glazing, making this a potentially worthwhile and rewarding process to research.

The enquiry grew out of the objectives set by the AHRC funded project to which this PhD is linked. A requirement of this larger project was for the PhD student to investigate efflorescence glazing and glassy ceramics to produce compositions suitable for low-cost 3D paste extrusion techniques. Limitations of the materials and processes developed during this practical investigation were identified relatively early on, necessitating this PhD to pursue an alternative line of enquiry for producing faience inspired, self-glazed ceramics suitable for 3D printing.

As such, the following research aim was identified:

To investigate 3D printing as a method of forming faience to be glazed using the cementation technique and to test its suitability for practical applications within art and design.

In order to give greater focus and direction to the enquiry, the following objectives were identified.

- Provide a historical and contextual review of Egyptian faience and to conduct a visual appraisal of traditional and contemporary faience artefacts to establish the benchmark standards of the various materials under development throughout the research.
- Present a contextual review of ceramic 3D printing to provide a general overview and to contextualise the research within the field of 3D printing materials/process development for creative applications in art and design.
- Through practical enquiry, investigate powder-binder 3D printing as means to form self-glazing ceramic bodies using the cementation glaze technique inspired by Egyptian faience.
- Develop a highly-vitrified or glassy body for 3D printable, single-fire ceramics.
- Use practical examples to test and evaluate the research findings.

Each of these objectives will now be reviewed in turn, reflecting upon what has been accomplished within this investigation and the extent to which the objectives have been met.

Provide a historical and contextual review of Egyptian faience and conduct a visual appraisal of traditional and contemporary faience artefacts to establish the benchmark standards of each material under development

The historical and contextual review of ancient Egyptian faience provided an introduction to the material and its origins, cultural significance and application as well as presenting essential information relating to the various faience compositions and glazing techniques. This was undertaken through a comprehensive literature review and by visiting museums (e.g. the Petrie Museum of Egyptian Archaeology, the British Museum and its archives and the Bristol Museum) and by consulting and sharing knowledge with experts (Dr Zahed Tajeddin and British Museum specialist staff). This information was instrumental in the ceramic material development work conducted through the research. A visual appraisal of traditional and contemporary faience artefacts was also conducted to establish the visual standard benchmarks of the various bodies under development throughout the research, a summary of which is as follows;

Characteristics of efflorescence glazing include a soft friable core with a distinctive glaze layer and a glossy surface typically turquoise blue in colour due to the addition of a copper compound. Faience objects glazed through cementation are characteristically bright blue in colour (due to the addition of a copper compound) and are coated in a rich and shiny glaze. The core of cementation objects can range from very soft and friable to a homogenous, dense and glass-like in structure dependant on the glaze powder ingredients and the firing schedule used to create it. Characteristics of application glazed faience objects include a range of brightly coloured glazes such as yellow, green, blue and red and a crazed glaze appearance.

These visual benchmarks played a key role in defining the choices made by the investigator throughout this enquiry, ensuring that the nature and extent of researcher participation remained clear and focussed upon the objectives of the project.

Present a contextual review of ceramic 3D printing to provide a general overview and to contextualise the research within the field of 3D printing material and process development for creative applications within art and design

A contextual review of ceramic 3D printing was undertaken to provide a general introduction into 3D printing technologies, specifically ceramic 3D printing and to contextualise the research in the field of 3D printing material and process development, particularly for creative applications in art and design. The contextual review included a review of literature and attendance at key 3D printing and ceramic events (e.g. TCT (Time Compression Technologies), trade shows and the British Ceramics Biennial in Stoke-on-Trent). This enabled the development of a sound understanding of the current state of the art in ceramic 3D printing and gave valuable insights into the particular challenges, limitations and opportunities associated with 3D printing in ceramics. These include, for example, the identification that current ceramic paste extrusion techniques have a relatively low resolution due to the size of the extrusion nozzle. Additionally, this process requires a soft and extrudable paste in order for it to flow freely through the nozzle and the resultant material tends not to be self-supporting and so limits the range of shapes that can be produced using this technique. Existing ceramic powder-binder printing processes offer a wider range of shape possibilities compared to that of paste extrusion, however these methods require several firings and post-processing stages. A motivation within the present research was to establish whether a glazed or glassy ceramic artefact could be produced with fewer firing stages. The high porosity of objects made using current ceramic powder-binder printing was also identified as an issue of the process during this stage of the research. This is primarily due to a lack of water and mechanical pressure during the fabrication of an object using the powder-binder process. A review of the faience literature revealed that some types of faience were homogenous and glass-like throughout, which showed significant potential for further investigation with a view for developing a 3D printable composition that would be much less porous compared to current ceramic 3D printing compositions. It is worth noting at this point that all current 3D printing processes have some limitations and issues e.g. in terms of material properties, surface finish, post-processing steps, and/or cost. Such limitations have been referred to as the “dirty secrets” of 3D printing [David Jarvis 2013]. For example, objects fabricated by the standard Z-Corp/3D Systems powder-binder printing process and plaster-based material have relatively high porosity, and the surface finish as-built is coarse and powdery. In plaster-based models, these issues are typically addressed by carefully sanding the surface of the object and then infiltrating the porous matrix with cyanoacrylate or epoxy resin to improve strength and density. The practical limitations of powder-binder printing - in particular, the strength, density and surface finish of 3D printed objects - carry over into the domain of ceramic 3D printing. As such these limitations represent some of the key challenges faced within this research project, as will be discussed in the forthcoming sections of this chapter.

Through practical enquiry, investigate powder-binder printing as a means to form self-glazing ceramic bodies using the cementation glaze technique, inspired by Egyptian faience

Using knowledge gained during the historical and contextual review of faience, initial experimental work was carried out to determine the rudimentary body and glaze powder compositions for cementation glazing. Initial trails used paste materials that were hand modelled into small test pieces as a quick and effective means of testing different body and glaze powder compositions. This later progressed on to preparing powdered compositions which were put into the powder binder printer and tested in terms of their 3D printability. Once an object had been 3D printed it was placed into a saggar, surrounded by the glaze powder and fired. After firing, the object was carefully removed from the partially sintered, yet still friable glaze powder. Development work primarily focused on improving the glaze formation, increasing the fired strength of the cementation body and reducing the glaze powder adhesion between the object and the surrounding glaze powder. Alternative metal oxide colourants were also explored through this practical investigation, which demonstrated that it was possible to produce cementation glazed objects in colours other than copper blue. Leading on from this practical enquiry, a glass-ceramic hybrid was also trialled for powder binder 3D printing. These practical investigations demonstrated that it was possible to create single-fired, self-glazed faience objects using 3D printing techniques as well as identifying certain challenges and limitations due to the particular nature of-this 3D printing process. These challenges and limitations will be discussed later in this chapter.

Additionally, 3D paste extrusion was explored as a method of fabricating faience, as it offers a low-cost and accessible alternative to other 3D printing technologies. Efflorescence and glassy-body compositions were explored during this stage and successfully demonstrated that this technique could be used to create small, low resolution objects that were single fired and self-glazed. The materials and methods developed through the paste extrusion trials provided a novel solution to the research question: ***Can 3D printing techniques be used to overcome the forming issues associated with traditional faience paste modelling techniques?*** However, in terms of overall scope and potential for practical exploitation, this technique is very limited in terms of object size, shape and object fidelity due to the combined effect of using a paste with poor working properties (i.e. low plasticity and short working time due to reaction between paste component materials) and a 3D printing process with a low resolution.

Use practical examples to test and evaluate the research findings

Having established the main faience body and glaze compositions, practical examples were used to further test and evaluate these materials. Initially small objects such as beads, tiles and amulets were created. These forms effectively demonstrated a compositions' suitability for the 3D printing process as well as providing essential information relating to shrinkage and deformation occurring as a result of the objects being fired. Once the material had reached a degree of competency, larger and more ambitious forms were created to further drive development. Examples of these forms include vessels, statuettes and lattice structures, including forms which would be difficult or impossible to achieve in faience by traditional modelling techniques.

Artefacts produced as practical examples were often inspired by ancient Egyptian art and design but were also heavily influenced by what had been learnt about the capabilities of the materials and 3D printing process. For example, the cementation process characteristically produces a core structure that ranges from very soft and friable to dense, homogenous and glass-like. The research identified that this range could be achieved on a single object of variable thickness, resulting in both translucent and opaque areas, creating an interesting contrast. In order to explore this property, practical examples that highlighted this contrast in core structure were designed, tested and evaluated. Additionally, this feature enabled very thin wall sections to be produced offering the potential to create fine and intricate shapes. This is especially significant for the cementation process as it has traditionally been limited to the production of very crude simple forms due to the poor working properties of the pastes used.

These objectives have provided direction and focus to the research, guiding the enquiry to address the research question and aim stated at the start of this chapter. Having reviewed the research findings and outcomes against the objectives it is now possible to identify the key contributions to knowledge made by this study.

Key contributions

The PhD project has successfully investigated, developed and tested to a 'proof of principle' stage 3D printable ceramic materials and methods for Egyptian faience glazing techniques; with a primary focus on the cementation glazing technique.

Cementation glazing was employed to produce a number of pieces, most notably a lattice pyramid that would have been impossible to create using traditional faience paste modelling techniques. The cementation method requires a high silica body composition, the resultant paste of which is very difficult to work by hand. This explains why historic and contemporary examples of faience glazed through cementation are limited to small simple shapes formed by hand or in simple moulds. This highlights the significance of the achievements made through this research enquiry. 3D printing with the cementation body has enabled a much wider range of shapes of greater complexity than traditionally possible. It was also successfully demonstrated that several other metal oxides could potentially be used as a colourant in this process such as bright green, purple and dark blue through the use of chromium, manganese and cobalt oxides. The ability to produce a clear glaze finish using this approach through the absence of a colourant was also demonstrated. There is potential for expanding the cementation colour palette further by staining the body (using commercially supplied ceramic stains) before firing in the saggar with uncoloured glaze powder to create a clear glaze layer on top. At present, there are no other historical or contemporary examples of cementation glazed objects in any other colour other than copper blue.

The cementation body composition developed here was found to be very strong in its green state compared to other 3D printable ceramic compositions. It is suspected that this is due to the composition being composed mainly of one material, i.e. 90% Fused silica, with a uniform particle size (75µm). The exact reason for this is unknown, however it is possible that a fairly uniform particle size of around 75µm would results in an open structure and may lead to more effective binding as a result of freer movement of the binding agent through the object during its fabrication. A 3D printable ceramic body with good green strength is advantageous to the 3DP ceramic process as it enables objects to be removed from the 3D printer and de-powdered with a reduced risk of breaking or damaging delicate features.

A characteristic of cementation glazed faience is a soft and friable core due to the refractory body components and a relatively low firing temperature. A limiting characteristic of objects produced using the powder-binder 3D printing process is a porous structure due to a lack of water and mechanical pressure during the build stage. The combined effect of these two characteristics has a negative impact on the overall strength of the material once fired resulting in a very delicate ceramic that is limited in terms of its end use application. However, this investigation found that the body strength cold be improved by pre-firing the cementation body to around 1200°C before firing in a glazing mixture without compromising the surface appearance. This two stage firing process is still less than existing powder binder 3D printing ceramics which typically require 3 or 4 firings. Infiltrating the body with colloidal silica also proved to be an effective way increasing the body strength. In ongoing research this approach is been developed further and has shown to also improve glaze consistency, object fidelity and reduce glaze powder adhesion.

Faience glazed through cementation can also be dense, homogenous and glass-like throughout, depending on several factors. This research has identified that object geometry (i.e. thin wall sections) and an extended 'soaking' time play a key role in transforming the soft and friable core to a dense-glass-like structure. Furthermore, when used in combination with the powder-binder printing process, this has the effect of reducing the overall porosity of an object.

Difficulties in controlling the glass-transformation property in cementation-glazed pieces and the inherent lack of strength in areas that did not transform, led to a different type of glassy ceramic material being successfully investigated. This material was based on a highly vitrified feldspathic composition which has an attractive semi-glossy surface appearance, similar to the ceramic body known as Parian. A typical Parian body is composed of china clay (30%) ball clay (10%) and feldspar (60%). Like faience, Parian compositions only requires a single firing, however the resultant surface appearance is semi-glossed rather than fully glazed. Parian bodies mature at around 1200°C and the core structure is homogenous and dense. The appeal of using this type of body in the powder binder printing process is that it could potential overcome some of the density and porosity issue inherent to this 3d printing process. Typical Parian bodies have relatively low plasticity due to the high flux content (60%). This component is fundamental in providing the semi-gloss surface appearance and dense homogenous core, therefore it cannot be removed or reduced. Previous research conducted at UWE has shown that low plastic ceramic compositions lend themselves very well to powder binder 3D printing, making Parian an attractive material for this process.

An efflorescence composition was developed for 3D paste extrusion which was then fired for 20 minutes in a microwave kiln. This process combined a self-glazing ceramic, a 3D printing technique and a novel firing method to successfully demonstrate an accessible and rapid means of fabricating 3D printing, glazed ceramics. Using this process, a glazed ceramic object may be 3D printed, dried and fired within 24 hours. This is a significant reduction in time compared to a conventional ceramic processes that use a typical tableware composition (i.e. earthenware) with a traditional forming technique (i.e. throwing) and a conventional firing method (i.e. in an electrical or gas kiln). This process may be particularly well suited for 3D printing demonstrations and workshops due to the accessibility of the 3D printing and firing equipment and the speed at which finished, small glazed objects such as jewellery can be produced.

The 3D printable faience recipes developed through this research are themselves key contributions. These recipes and what makes them successful will now be discussed.

Cementation body and glaze composition for powder binder 3D printing

3DP Body recipe 1

Fused silica – 90%

Potash feldspar – 10%

Maltodextrin– 12.5% (addition)

Glaze powder recipe 4

Silica: 32.2%

Calcium hydroxide: 46.9%

Sodium carbonate: 15%

Copper carbonate: 5.9%

Sodium Chloride: 4%

The cementation body is composed mainly of fused silica (90%) and as a result is very strong in its green state, making this composition particularly well suited to powder binder 3D printing. Part of this 3D printing process involves the objects being de-powdered and handled. Bodies with poor strength often result in breakages at this stage, therefore compositions that are stronger (such as the cementation body) can potentially be used to create more delicate and intricate shapes. Additionally, the use of fused silica as opposed to flint provides a safer alternative to the person operating the 3D printer as it is less harmful if the powder were to be accidently inhaled.

The glaze powder developed within this research is made up of 5 components. Upon firing a series of complex reactions take place between these minerals and those within the cementation body. Some of these reactions have been hypothesised both within this research and by the wider research community, yet in truth they are not fully understood.

Nevertheless, this investigation has demonstrated that value of using an empirical and iterative approach, which has resulted in the development of successful “proof-of-principal” practical outcomes.

Efflorescence paste for 3D extrusion

Efflorescence paste recipe

Soda feldspar: 36.2%

Flint: 23.8%

China clay: 30%

Soda ash: 10%

Stain: Approx.2.5% (% addition)

The efflorescent recipe developed for 3D paste extrusion contains a large percentage of china clay, which is not typical of traditional faience compositions. It is however a common component in contemporary faience bodies as it drastically improves the workability of the paste. China clay is an essential component for ceramic paste extrusion as it enables the material to flow through the nozzle orifice and once deposited, ensures that the material retains its shape and supports the weight of subsequent layers. The key to the success of this composition is that the body includes enough china clay to facilitate 3D extrusion, whilst maintaining the overall chemistry of the composition to enable successful efflorescence glazing to occur.

Parian composition for powder binder 3D printing

3DP Parian Body

Molochite – 13%

China clay – 17%

Nepheline Syenite – 70%

Maltodextrin– 12.5% (addition)

This composition was adapted from a typical Parian recipe, removing the highly plastic ball clay component and reducing the percentage of china clay. Molochite was added as it is essentially the same minerology to china clay, however is now no longer plastic as a result of being calcined. Nepheline Syenite was selected for its whiteness and low thermal expansion, and maltodextrin was added as an essential component for the powder binder process.

Secondary contributions

In addition to the primary contributions described in the previous sections, the PhD student also made some secondary contributions which relate to the larger AHRC funded project linked to this PhD. This larger project has primarily explored the efflorescence and application glazing methods in combination with powder binder 3D printing technologies. A summary of this work is presented in appendix 4 of this thesis. The PhD student made a significant practical contribution to the larger project during the early stages of her PhD, working under close supervision of her supervisors. This included helping to develop and test to proof of concept stage both efflorescent and application glaze 3D printed ceramics, and contributing to the identification of capabilities and limitations of these processes. This earlier, formative phase helped to provide the necessary knowledge, practical experience and confidence that was needed to undertake the independent research project which constitutes the primary contribution of this thesis.

Having identified the principal contributions made by this project, it is now possible to discuss the impact and implications of the research beyond academia.

Sharing knowledge with other research specialists: UCL, and the Petrie museum

Discussions have taken place (October 2014) with Zahed Tajeddin, researcher in archaeology at University College London and the Petrie museum on emerging results from the research. Tajeddin has recently completed his PhD research into Egyptian faience including using CAD-CAM techniques (hot wire cutting) to fabricate moulds to form large faience items. Interesting discussions were held on the different methods, materials and the chemistry involved. There is potential to extend these discussions with a view to developing future collaborations, in particular regarding possible museum applications for this research.

Impacts beyond academia

In addition to academic benefits, the research is expected to have significant impact beyond academia. This has already begun to happen in the following ways.

Research has been presented at IS&T (Society of Imaging Science and Technology) Digital Fabrication conferences in the USA in 2013, 2014 and 2015, which attracts a significant proportion of delegates from the 3D printing industries as well as from academia.

Research has been presented at the Impact 8 printmaking conference in 2013 which attracted a significant proportion of delegates from professional practice in art, design and craft industries.

The PhD research contributed to a practical demonstration/ workshop on 3D printing as part of a residency at the museum of Art and Design, New York in November 2013.

The PhD student participated in CFPR demonstration at the AHRC Digital Transformations Moot event (London, November 2012) which attracted delegates from the museums, creative arts, cultural heritage sectors and beyond.

This research has made a unique contribution to research in 3D printing that brings together old and new technology, by creatively combining ancient Egyptian-inspired ceramic materials with contemporary computer-aided design and digital fabrication technologies. The research successfully demonstrates proof of principal of 3D printing self-glazing ceramics and points to significant opportunities for future research.

Having discussed the key contributions made by this thesis, further opportunities to develop this research will not be suggested.

Opportunities for future research

This research has identified opportunities to further develop and extend this enquiry in the future. One general limitation of ceramic powder binder printing is that the finished object is not as dense or strong as conventionally formed ceramics. Future research will investigate techniques from the field of foundry ceramics such as the use of colloidal silica based binders to add density and strength to the 3D printed ceramic. This would be of particular benefit to the cementation materials and method developed within this research and preliminary trials using colloidal silica to infiltrate pre-fired cementation compositions have shown some promising results, increasing object density by approx. 50% and improving the surface finish. This and other potential post processing techniques will be investigated further in future research [e.g. applying a siliceous slip to smooth out rough surfaces, whilst maintaining the compositional requirements for faience glazing].

The vitreous feldspathic ceramic composition also showed significant potential for further development. However, one of the challenges identified through the investigation was the observation that this material had a high shrinkage rate (*ca*.35%). It is possible that the shrinkage could be reduced by investigating different fluxes and fillers, however it is important to acknowledge that a consequence of reducing the porosity of a ceramic body through virtification is that the resultant body will always be subject to a significant degree of shrinkage.

Future research will also explore the potential for 3D printed faience and faience-like materials to be exploited within the museum and heritage sector. This is a promising area of interest identified through the contextual review and networking activities during the research.

For example, to create replica museum artefacts in order to enable museum visitors to engage with historic artefacts which are too fragile or valuable to touch. Future research will also investigate the potential to develop and extend the research to a wider range of art and design applications - such as 3D printed ceramic jewellery and small-scale art objects - and finally, to further disseminate research findings via CFPR contacts within the 3D printing industry.