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LOW TECH WASTE 3D PRINTING

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ABSTRACT

Binder jet 3D printing of geopolymers is a newly developed manufacturing technique that combines a material with a low carbon footprint with a material-saving processing. In this work, the embodied energy of the printed building parts is further decreased by replacing the virgin silica sand with waste materials from local stone quarries. The use of the quarry waste in 3D printing could help to keep the business of small quarries running, since they face severe problems with the disposal of the waste. Test bars were printed with different grain sizes and tested on flexion and compressive strength, density and accuracy. The results show that the material is strong enough to be applied in structures loaded on compression only. 3D printing of quarry aggregates could help to valorise the locally available material and enhance the use in classical techniques as well, in order to reduce the amount of deposited material.

KEYWORDS

Gneiss quarry waste, Geopolymers, 3D printing

INTRODUCTION

The construction industry is the largest emitter of anthropogenic CO_2 and more than 40 % of the resources consumed worldwide are used for construction (Horvath, 2004; Ioannidou et al., 2017). In the last decades the operational energy of buildings was reduced significantly for example by better insulating the buildings (Hegger et al., 2012). What is left is the embodied energy in buildings, coming from the production, transportation and end of life of the building materials. The embodied energy can be reduced on one hand by using less material, and on the other hand by using building materials with a low carbon footprint. Using smart design enables the design of structurally optimised building parts, which can reduce the amount of materials used. 3D Printing and additive manufacturing techniques make the implementation of the often complex optimised shapes possible. If these techniques are combined with materials with a low carbon footprint, the overall reduction of the embodied energy is even higher (*cf.* Figure 1).

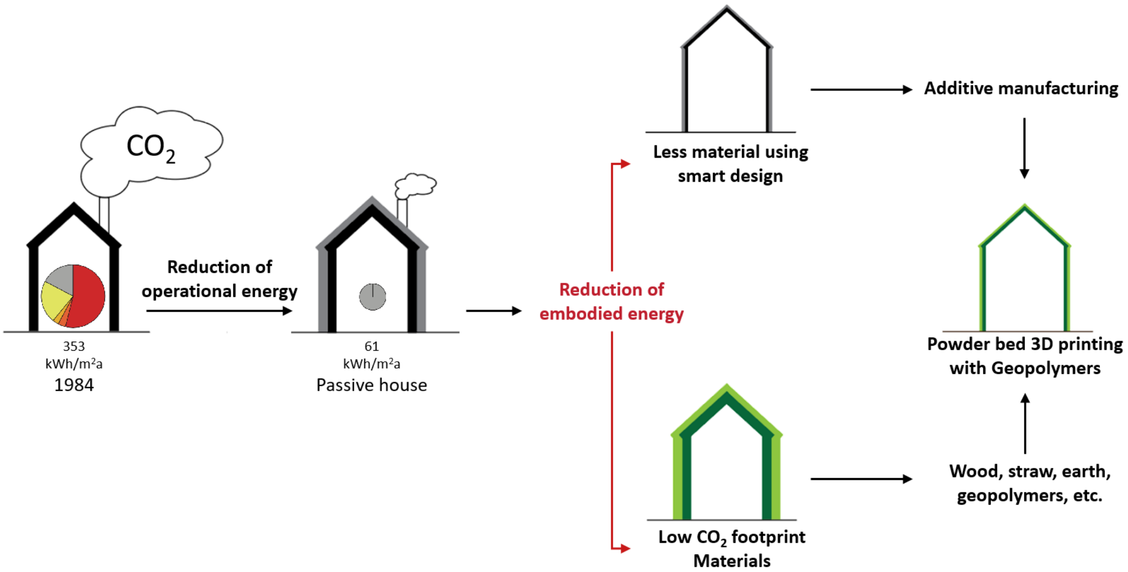
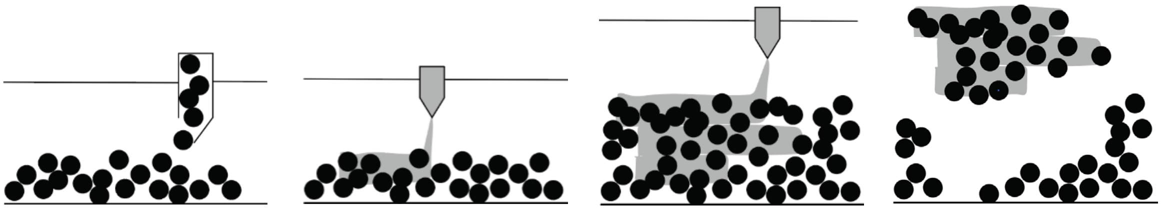


Figure 1: Reducing the embodied energy of buildings by combining additive manufacturing techniques with low CO_2 footprint material

The 3D printing method of choice is powder bed 3D printing because it enables the printing of overhangs, which is necessary to print the complex structurally optimised parts. In powder bed 3D printing, a layer of powder is spread and bond with the binder in selected places. By repeating these steps, the print is built up layer by layer (*cf.* Figure 2).



Sand spreading Binder application Layer by layer printing Demoulding

Figure 2: Working principle of powder bed 3D printing

Previously, it was shown that geopolymers can be used as a binder in powder bed 3D printing (Voney et al., 2021). Geopolymer is an amorphous mineral material, synthesised from an aluminosilicate source activated by an alkaline solution. Geopolymer has a lower CO_2 footprint than cement (Komkova et al., 2022) and the prints are strong enough to print structurally optimised building parts. Therefore, geopolymer as a binder in powder bed 3D printing is the ideal combination of a material with a low CO_2 footprint in a material saving manufacturing technique. However, as aggregates in the powder bed, sand is still used. Sand is getting scarce and its depletion creates immense ecological damage. For this reason, in the present work, the replacement of silica sand in powder bed 3D printing was investigated. The silica sand is replaced by waste materials from local stone quarries in Ticino, in the south of Switzerland.

The exploitation of natural stone, mostly gneisses, is an important economic sector in the valleys of Ticino, in the south of Switzerland (Schenker et al., 2018). As described in Schenker et al. (Schenker et al., 2020), in the last decades, the local quarries faced severe economic difficulties due to the rules on the disposal of the quarry wastes and the territorial planning that regulates the structure of quarries and inert landfills. This puts high pressure on the profitability of the quarries, as up to 40% of the extracted material is waste, leading to high disposal costs. The waste occurs at different stages of the production: it consists of extracted stone with insufficient quality (e.g. veins) cutting leftovers or fine sawing dust.

The quarry waste can be used as aggregates in concrete or street pavements (Kore et al., 2016; Wu et al., 2009). In the meantime, it was shown by (Schenker et al., 2020) that the quality of the quarry waste material extracted in Ticino is good enough for regular concrete production.

Unfortunately, nowadays it is cheaper to import aggregates with better quality (Borbon-Galvez et al., 2021). Therefore, all the waste needs to be landfilled, which leads to environmental/nature problems. Since the available space for landfills is scarce (CantoneTicino, 2018), it is cheaper to export the aggregates to Italy and landfill them there (Borbon-Galvez et al., 2021).

The use of the waste materials in 3D printing would help to reduce the amount of material that needs to go to landfill. Additionally, by applying the local waste material in a new technique, the waste is valorised and the use of the material could be promoted also for other applications. Using higher quantities of the local material could help to keep the business of small quarries profitable.

MATERIALS AND METHODS

Powder bed

Materials sourced from two quarries in different regions of Ticino were used in this work: from Valle Maggia (Bettazza, B), and from Cresciano (Ongaro, O). The compositions of the different materials are summarized in Table 1. Two different grain sizes were used from both materials, < 0.3 mm, called fine and 0.7-1.2 mm, called coarse. Additionally, a mix between the two fractions with the highest packing (40% fine and 60% coarse) was prepared, referred to as "optimized mix" in the following.

Table 1: Compositions of gneisses from different quarries (Schenker et al., 2018)

	Bettazza (B) Valle Maggia V %	**Ongaro (O)** Cresciano V %
Quarz (qz)	30	25
Potassium feldspar(ksp)	10	5
Plagioclas (pl)	40	43
Biotite (bt) Mica	15	10
Chlorite (chl)	2	1
Zoisite (zo) (/allanite (all))	1	1
Titanite (tt)	2	5
Anfibolo (anf)		10

As an aluminosilicate source 20 wt% Metakaolin (Metastar501 from Imerys, here referred to as MK) with a mean grain size d_{50} of 4 µm (measured with laser scattering, Horiba Partica LA-950) is added to the powder bed. The SiO_2 and Al_2O_3 contents of the Metakaolin are 51.63 wt%, and 44.37 wt%, respectively, and were determined with XRF.

Printing solution

As an activating solution a potassium silicate solution was used. The solution was produced from deionized water at 20 °C, KOH in pellet form sourced from Sigma Aldrich, and silica gel in powder form (Davisil grade 635, Sigma Aldrich). The H_2O/K_2O and SiO_2/K_2O ratios were 13.9 and 1.6 respectively. The specific density of the solution (1.42 g/cm^3) was measured with a Densito 30 PX (Mettler Toledo).

Powder bed 3D Printing

To implement the geopolymer in the powder bed 3D printing, a binder jet method is used (Lowke et al., 2018). Metakaolin is mixed with the quarry material and serves as powder bed, distributed in fine layers (*cf.* Figure 4). In distinguished places, a potassium silicate solution is printed on top of the powder bed layer reacting with the metakaolin and forming the geopolymer binder. Repeating these steps, the printed part is built up layer by layer and can be demoulded from the powder bed after finishing the print.

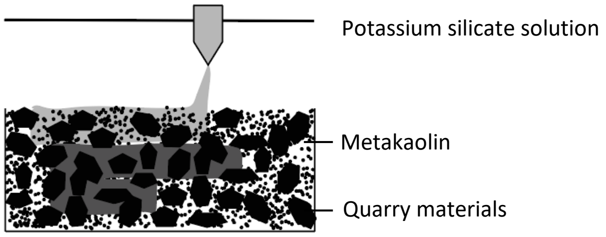


Figure 3: Binder jet 3D Printing with geopolymer and quarry materials

RESULTS

The density was determined by envelop density analysis in a Geopyc from Micrometrics, the results are visualized in Figure 4.

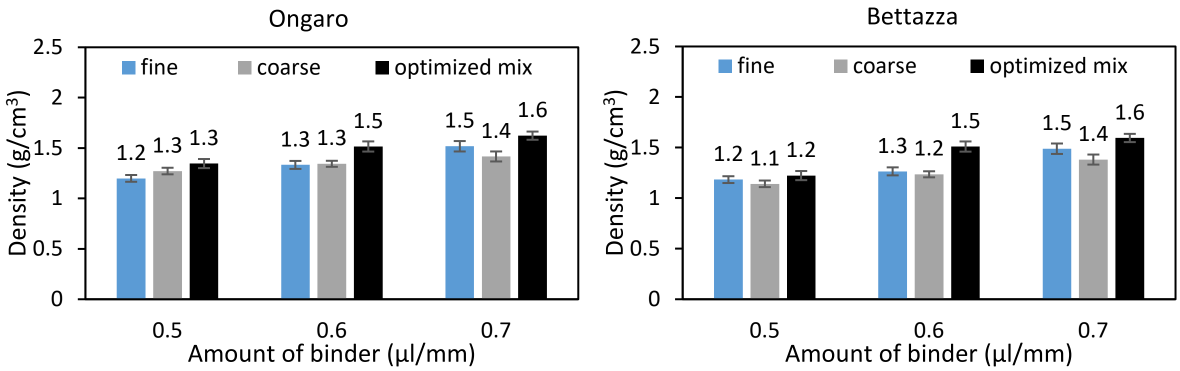


Figure 4: Density of printed parts measured with Geopyc

The width, height and length of the printed samples was measured with a calliper. The width corresponds to the y-direction in the printer, the height and the length to the x- and z-direction respectively. The accuracy of the print in all directions was calculated from the targeted length l_0 and the measured length l_{meas} in the corresponding direction according to Equation 1.

$$Accuracy\ (\%) = \frac{|l_0 - l_{meas}|}{l_0} * 100\% \qquad \text{Eq. 1}$$

The accuracies are plotted in Figure 5.

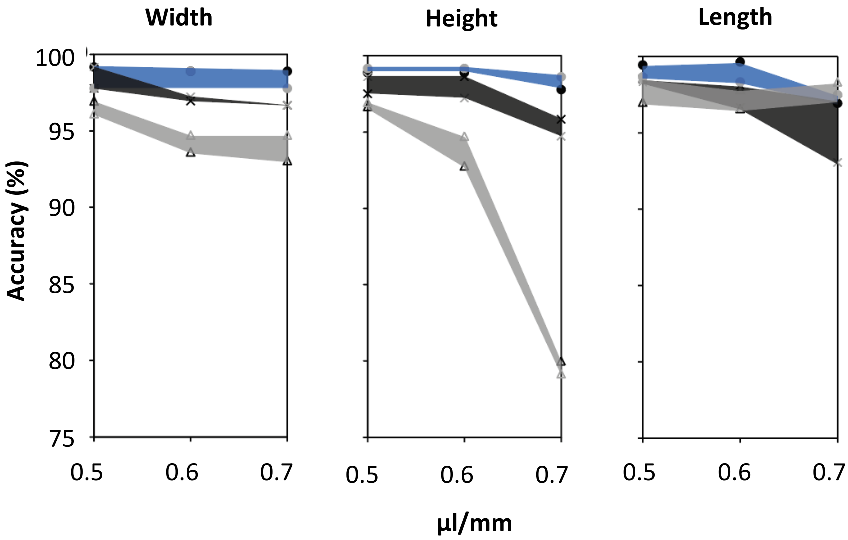


Figure 5: Accuracy of printed bars on quarry material from Ongaro and Bettazza. The colours blue, grey and black represent the different powder beds fine, coarse and the optimized mix.

The flexion and compressive strength of the printed parts was assessed with a mechanical press (Matest, Switzerland) equipped with a 50 kN cell, applying 0.1 kN/mm perpendicular to the printing planes, according to ASTM C349 (*cf.* Figure 6 and Figure 7).

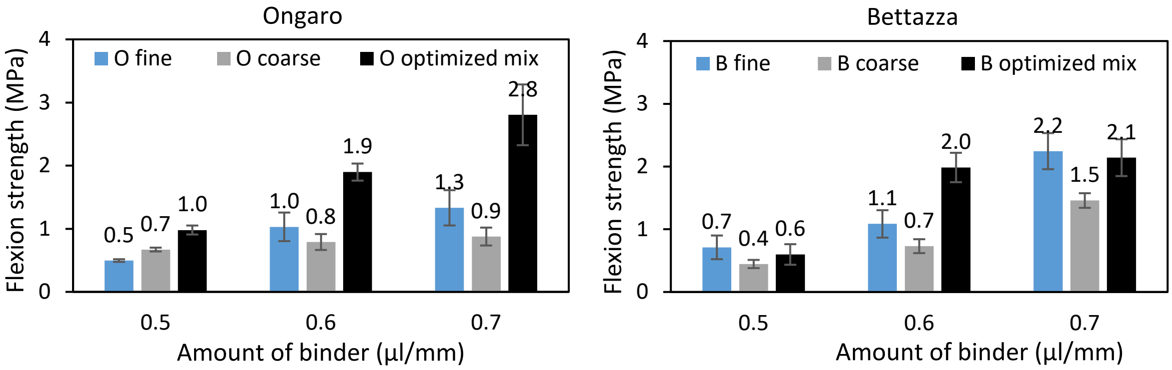


Figure 6: Flexion strength of bars printed on quarry material from Bettazza and Ongaro

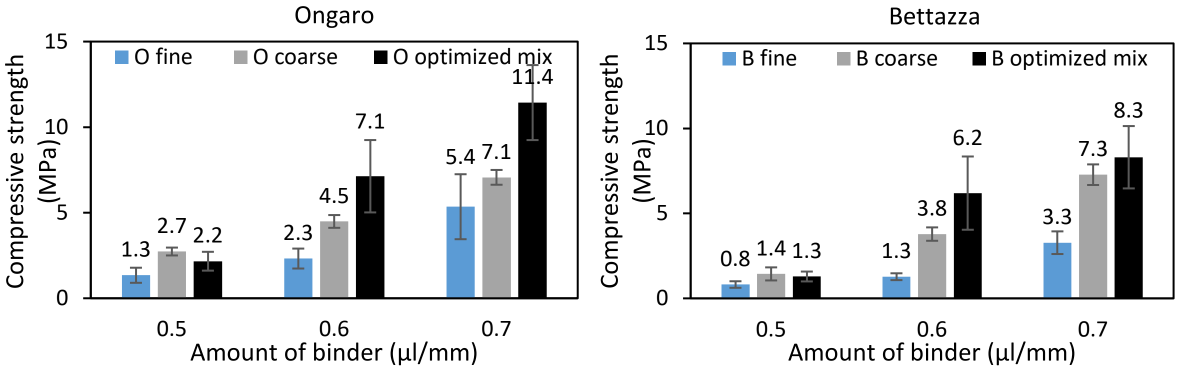


Figure 7: Compressive strength of bars printed on quarry material from Ongaro and Bettazza

DISCUSSION

Overall, the density of the printed parts increases with increasing printing liquid from 1.1 g/cm^3 to 1.6 g/cm^3, which also leads to higher compressive and flexural strengths. In Figure 8, the compressive strength is plotted as a function of the printing liquid with a linear fit for each grain size. The slope of the linear fit depends on the grain size and grain size distribution. Coarse grains improve the compressive strength compared to fine grains. This could be due to the facilitated penetration in the powder bed with coarse grains. At the same layer height, with smaller grains, the liquid is not able to fully penetrate to the lower layer, leading to less connected layers and a lower strength. This is supported by the cross-section views in Figure 9, in samples printed with fine aggregates, printing layers are clearly visible. The drawback of the enhanced penetration on powder beds with coarse grains is the loss in accuracy. Especially in z-direction (height), where prints with 0.7 µl/mm only reach 80 % dimensional accuracy, whereas samples on fine sand are close to 100 % (*cf.* Figure 5).

Printing on a powder bed with optimized packing (40% fine + 60% coarse) clearly increases the strength of the prints. The mix of the different grain sizes leads to a dense packing and limited penetration, therefore increasing the strength and keeping a high precision.

The sensible difference in strength between the material of the two different quarries is likely due to the different concentrations of mica. The elevated mica content in the Bettazza waste lowers the permeability and hinders efficient penetration of the binder. In any case, both materials achieved compressive strengths that would be suitable for compression only structures.

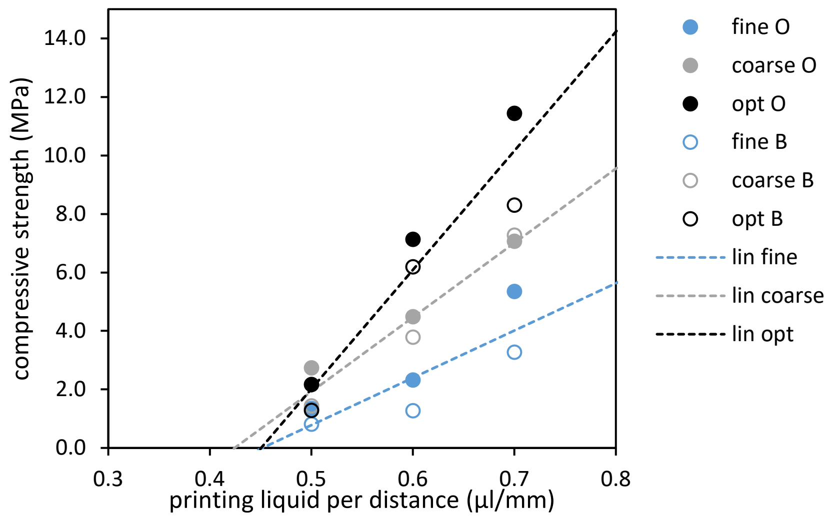


Figure 8: Compressive strength of samples printed with varying µl/mm on different powder beds. The dotted lines represent the linear fit of samples printed on the same powder bed.

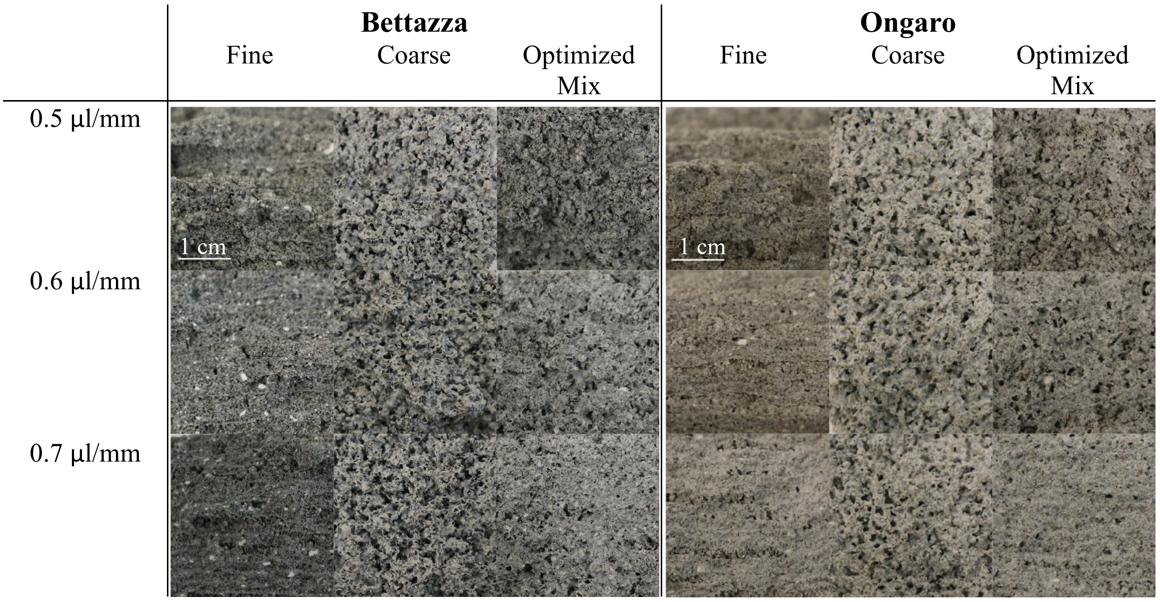


Figure 9: Cross sections of Bettazza and Ongaro samples

In general, the accuracy of the printed parts is very high. However, the higher amount of binder and, consequently, higher strength, comes with a decreased accuracy, especially in width (y-direction). Powder beds that hinder the penetration (fine grains), also hinder the liquid to leak from the original form, therefore their lower strength comes with higher accuracy.

The accuracy of the mixed samples lies in between the coarse and the fine grains, which raises the assumption that the penetration is better than on the powder bed with fine grains. This could be due to the influence of the metakaolin on the packing of the dry state of the powder bed. The platelet like shape of metakaolin might hinder the dense packing of the powder bed, leaving larger pores for mixed powder beds than for mono-sized small powder beds.

Environmental impacts

The environmental impacts in terms of global warming potential (GWP) of 1 m^3 of 3D printed geopolymer were estimated using the IPCC2013 method, where the life cycle inventories were collected from the Ecoinvent 3.8 database.

The substitution of silica sand with quarry waste in geopolymer binder jet 3D printing reduces the GWP by nearly 8% (Figure 10 left). Furthermore, comparing the current mix design with a smart 3D printed formwork where the binder is made of phenolic resin and phenyl isocyanate (Agustí-Juan et al., 2018), the carbon intensity index of the low tech waste 3D print is significantly lower (Figure 10 right).

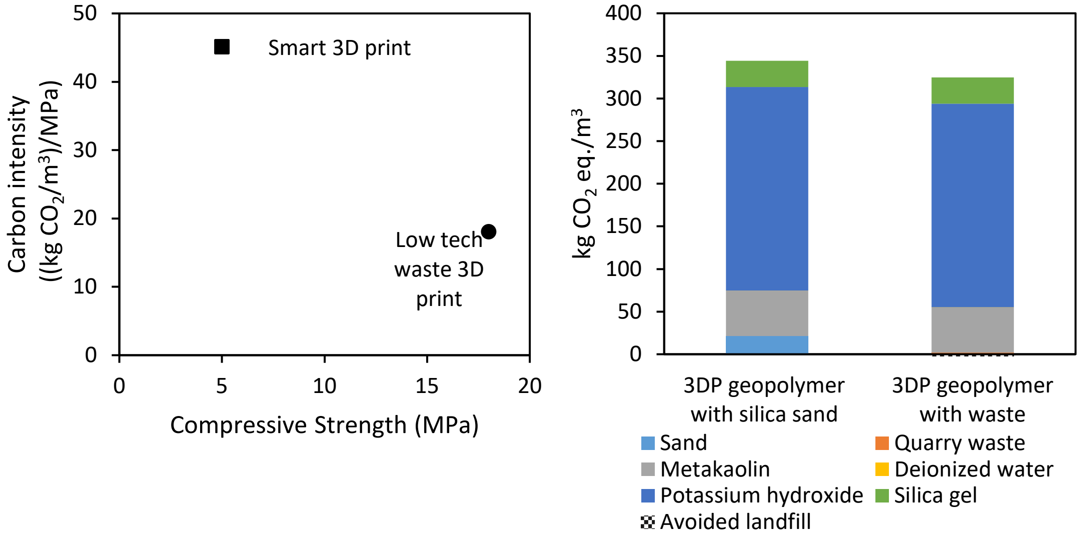


Figure 10: Left: GWP of 1 m^3 of 3D printed (3DP) geopolymer with quarry waste compared to 3D printed geopolymer with silica sand. Right: Carbon intensity index of Smart 3D printed formwork and Low-tech waste 3D printed geopolymer.

CONCLUSION

The quartz sand in powder bed 3D printing can be replaced with quarry waste aggregates with a slight loss in compressive strength (18 MPa with quartz sand versus 11 MPa with quarry waste). The compressive strengths reached with quarry aggregates printed with geopolymer powder bed 3D printing are still excessing the values of parts printed with a conventional phenolic resin /silica sand based powder bed print and are sufficient for self supporting structures. The pictures in Figure 9 show that there might be some improvement potential in adapting the layer height to the grain size/grain size distribution of the powder bed. In terms of accuracy, the parts printed with quarry aggregates are comparable to parts printed with quartz sand. The slight difference in compressive strength between the two in detailed tested quarries could arise from the varying mica content. To strengthen this hypothesis, more tests should be conducted on gneisses with higher and lower mica contents.

To show the potential of the achievable details, the element in Figure 11 was printed.

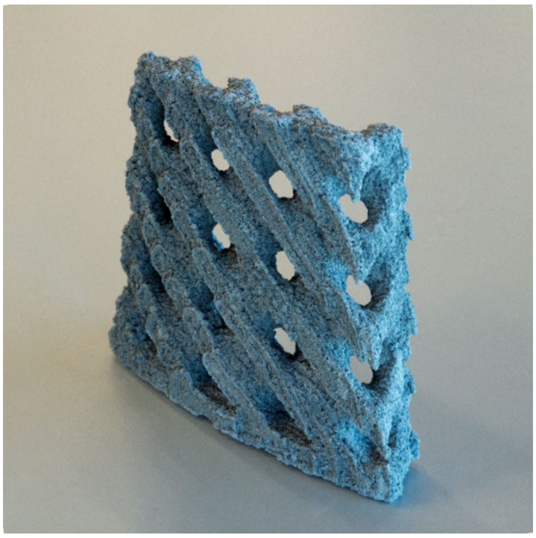


Figure 11: Complex shape printed with quarry waste (approx. 20 x 20 x 6 cm^3)

The use of different grain sizes or grain size distributions might tackle different applications. A powder bed with optimized packing leads to maximized compressive strength of the print, which is required in many construction applications. However, there are other applications where the strength is secondary and a low density is required, for example lightweight or insulation parts. Then, powder beds with larger grain sizes could be used. The variability of the grain size not only allows the control of the strength and the density, it further leads to different textures, which could be of interest from a design perspective (*cf.* Figure 12).

Figure 12: Texture (side view) of prints on fine (left), mix (middle), and coarse (right) Bettazza grains

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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