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Biomass concrete for low carbon buildings: A circular economy case study in South Africa

A Lord[1], A Menardo[2], C van Reenen[3*], S Lamb[1], G Nduna[4], P Mafuwe[4], T Van Mele[2] and P Block[2]

[1] nonCrete Pty (Ltd), Cape Town, South Africa
[2] Block Research Group, ETH Zurich, Zurich, Switzerland
[3] Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa
[4] One-Nil Construction, Cape Town, South Africa

*E-mail: cvreenen@csir.co.za

Abstract. This paper presents a case study of a low carbon affordable building in South Africa, utilizing innovative biomass concrete for bricks, funicular floor and roof modules that are optimized in terms of geometry and mix design to reduce their global warming potential (GWP). The objective is to address the urgent need for more sustainable construction practices and to demonstrate circular economy principles by incorporating chipped biomass from invasive alien plants (IAPs) as a supplementary ingredient in the concrete mix, leading to what has been labelled *nonCrete* (NC). This approach not only mitigates the environmental impact of traditional concrete production but also contributes to the management and eradication of IAPs in the region, which affect the natural water cycle, compete with local flora and fuel frequent wildfires. The focus of this paper is to demonstrate the potential environmental and social impact of NC use in construction in real-world applications through a case study. The design of the floor system, supported by rigorous material tests leading to its accreditation on the local market, indicates that the use of NC has the potential to lower greenhouse gas emissions (GHG) associated with construction, while still fulfilling all the necessary engineering standards and facilitates local job creation. This work is intended to serve as a pivotal step towards more sustainable building methodologies in South Africa and demonstrate circular economy principles in practice.

1. Introduction

Traditional reinforced concrete, a staple in construction, has a significant carbon footprint due to the energy-intensive production of cement and steel reinforcing. Furthermore, conventional concrete requires large amounts of non-renewable resources like sand and virgin aggregates . In response to the growing environmental concerns, there has been an increasing interest in developing sustainable alternatives for the circular economy based on three core principles: to eliminate waste and pollution, to continuously circulate products and materials, and to regenerate natural ecosystems. These principles help support a low-carbon, sustainable, and inclusive economy, addressing key challenges and unlocking new opportunities for growth and development .

1.1. Context and problem statement

The Cape region in South Africa provides more than 50% of the country's water. However, many of its riverbanks have been invaded by invasive alien plants (IAPs), such as Eucalyptus, Acacia and Pinus species , affecting the already strained water supplies , competing with the local flora, and fuelling wildfires .

Local authorities have committed to clearing about 11,000 hectares of IAPs by 2025, not only reducing the environmental strain but also providing green, gender inclusive jobs . The mass eradication of IAPs has resulted in a huge amount of biomass that releases previously absorbed carbon back into the atmosphere, unless permanently bound, for example, within building components.

While facing environmental challenges, South Africa also suffers a significant housing shortage and high unemployment . The South African Department of Human Settlements, in their recent White Paper, promotes the use of innovative building technologies to support sustainable human settlements , however, there is generally a low uptake of novel building technologies, in part due to a lack of knowledge and skills transfer around innovation.

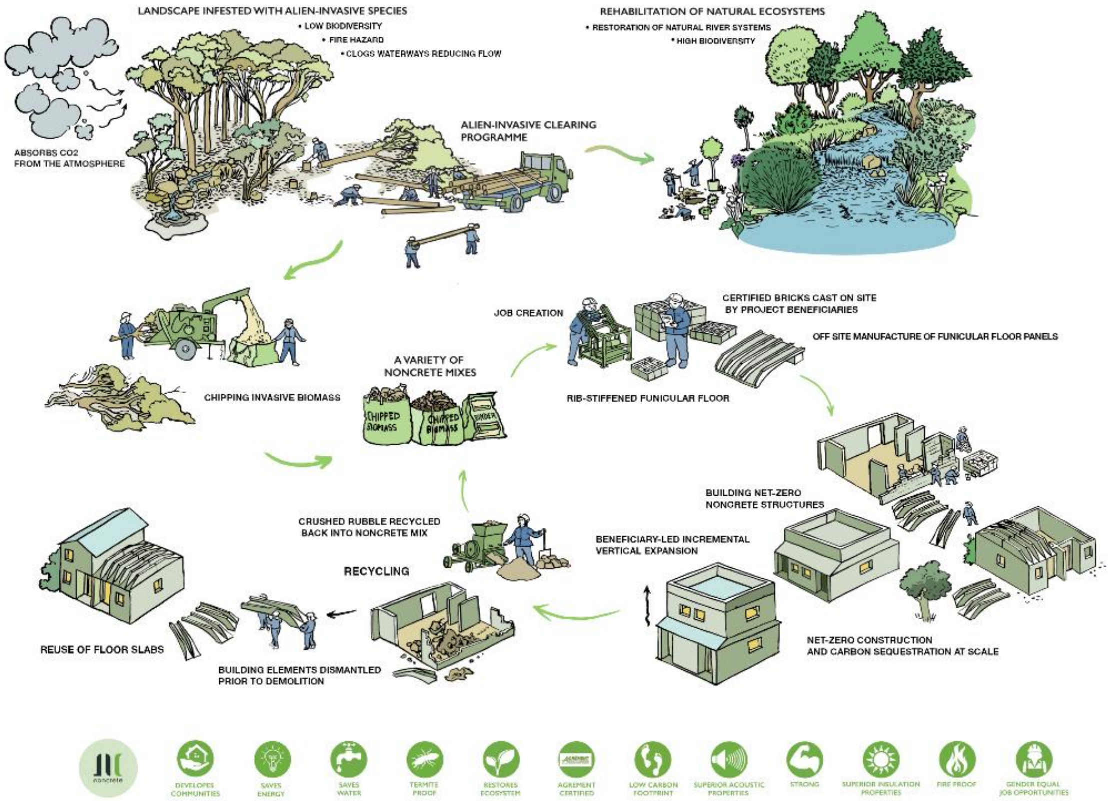

Figure 1. The circular economy of *nonCrete* production.

1.2. Objectives

Considering the need for sustainable infrastructure in human settlements in South Africa, together with the need to eradicate IAPs and deal with the resultant bio waste, and to create employment, there exists an opportunity for an innovative solution.

The objective of this paper is to present the application of a novel biomass concrete, labelled *nonCrete* (NC), for the production of bricks and unreinforced funicular floors and roof modules

(**Figure 2**). The floor and roof element are optimized in terms of geometry and material mix to reduce the global warming potential (GWP) and can be used in low carbon affordable buildings in South Africa. This approach not only mitigates the environmental impact of traditional concrete production but also contributes to the management of IAPs and the creation of local job opportunities, supporting a local circular economy, as illustrated in **Figure 1**.

Figure 2. View of a 1 m wide section of completed nonCrete floor and bricks.

2. Materials and Methods

First, the key features of the NC biomass concrete mix and the geometry of the NC floor or roof panels are presented here, followed by an assessment of the impact on embodied carbon. Then a case study is analysed, namely the construction of a crèche in a rural settlement in Elandskloof, South Africa.

2.1. Lightweight Biomass Concrete Mix Designs

Cape Town-based company *nonCrete* developed a process by which IAPs are shredded into wood chips and bound with cement and admixtures into a structural mix that is 45% lighter than conventional concrete, as well as a non-structural filler that is 70% lighter than conventional concrete. The recipe used for the bricks is also lightweight, at 43% the density of normal concrete. By using large amounts of locally available and intrinsically renewable biomass, the use of non-renewable resources like sand and aggregate is drastically reduced . At the same time, the carbon captured in the chips is permanently locked into the product, in a process referred to as carbon sequestration.

The potential carbon-reducing effect of the product used in the building envelope extends to the operational phase of the building, since the excellent insulating property of NC translates into lower heating and cooling energy demands.

2.2. Rib-stiffened funicular floors

As a result of the low density and reduced use of aggregate in the NC mix, the compressive strength of all mixes, ranging from 6MPa to 12MPa, is significantly lower than that of conventional concrete used in building structures. However, by exploiting the properties of the materials, *nonCrete* and the Block Research Group at ETH Zurich developed a hybrid floor system where the structural mix is used in a completely unreinforced and prefabricated rib-stiffened vaulted shell (**Figure 3**, left) while the non-structural filler is applied in-situ to build a walkable surface (**Figure 3**, right). As a result of the vaulted geometry, the entire structural section undergoes purely compressive stresses and of a very low magnitude: a perfect application for a low-strength material.

2.3. Structural performance

To verify the validity of the form-finding assumptions and of the structural analysis, load tests were carried out by independent third parties on full scale portions of the floor, as well as of the cavity brick wall used in the perimeter walls of the crèche.

Both NC elements were then tested for performance at high temperatures under sustained loading; the results verified that they fulfil (and indeed exceed) the most stringent fire resistance criteria for real building applications, namely mechanical Resistance, Integrity and thermal Insulation (REI).

Figure 3. Rib-stiffened shell of structural mix (left) and non-structural in-fill creating walkable surface (right).

2.4. Fabrication

Offsite modular prefabrication was identified as the best strategy to ensure a cost-effective, speedy and quality-assured delivery of the structural skeleton of the floor, combined with a more conventional finishing strategy on site. The funicular floor or roof panels are manufactured in two halves (see **Figure 4**) for ease of handling, and then joined at the apex and covered with non-structural filler mix on site.

The panels are currently produced in standard sizes, meaning that the overall economic and environmental impact of the hand-made formwork – which has already been used tens of times without deterioration – is negligible, as it gets amortised over many slabs.

Figure 4. The funicular floors manufactured in halves and transported to site for assembly and finishing.

2.5. Embodied Carbon

The funicular floor system produces lower GHG emissions relative to conventional floors on two fronts. First geometrically, by using a 60 mm thick, completely unreinforced shell (plus filler) in place of a solid flat 200 mm thick reinforced slab that would be needed to span 5 m reducing weight and material usage by approximately 30%. Secondly, considering the species and quantity of chips used, the amount of biogenic carbon sequestrated (calculated using) more than offsets the Cradle-to-Gate emissions (stages A1-A3) associated with the Portland composite cement blender (taken from average values from) and with the mechanical processing of the wood chips, resulting in negative embodied carbon coefficients (ECC) and precisely -86 $kgCO_2eq/m^3$ for the structural mix, -178 $kgCO_2eq/m^3$ for the filler and -96 $kgCO_2eq/m^3$ for the brick mix respectively.

Contrary to structural timber, which is assumed to go to landfill at the end-of-life (stages C1-C4) and thus release the previously stored CO_2, the NC products can be crushed and re-used in future NC mixes or downgraded as rubble, either way storing their biogenic carbon content in perpetuity.

2.6. Case Study Building Design

A pilot project, in the form of a créche, in the Elandskloof valley, some 170 km from Cape Town, was identified to demonstrate the various benefits of the circular economy framework (**Figure 1**) and of the materials and building systems described herein (**Figure 2**).

Following a successful land return post-Apartheid, the residents of Elandskloof, - a marginalised rural community – returned to rebuild on their land. However, with little government support, progress has been slow and they still live in makeshift timber and corrugated iron structures. These are vulnerable to fire and pests, are structurally unsound and offer little protection against the harsh climate. In the last 25 years, alien vegetation has invaded the river and surrounding valley – depleting water and destroying biodiversity. These factors offer an appropriate site to demonstrate the environmental and social benefits of NC products in meeting the infrastructure and employment needs of South Africa.

The single-storey crèche was the result of a participatory exercise, in which the local community actively engaged in the co-design process. This included three facilitated co-design workshops and hands-on exposure to both the materiality and the key geometric features of the NC products (see **Figure 5**). The project also aimed to up-skill Elandskloof residents in the production of the NC components as well as in their assembly on site, to create low-tech, labour-intensive job opportunities in the ecological rehabilitation efforts associated with IAPs clearing.

Figure 5. Co-design process and model of resultant design.

The resulting co-design, with executive plans drafted by Stuart Thompson Architecture, was a pragmatic 8 m x 8 m plan with load-bearing cavity walls made of NC bricks, with a central classroom featuring the NC funicular floor spanning the 5 m open space (see **Figure 6**). The slab above the ancillary alcoves on the sides is instead executed for simplicity in nominally reinforced conventional in-situ concrete.

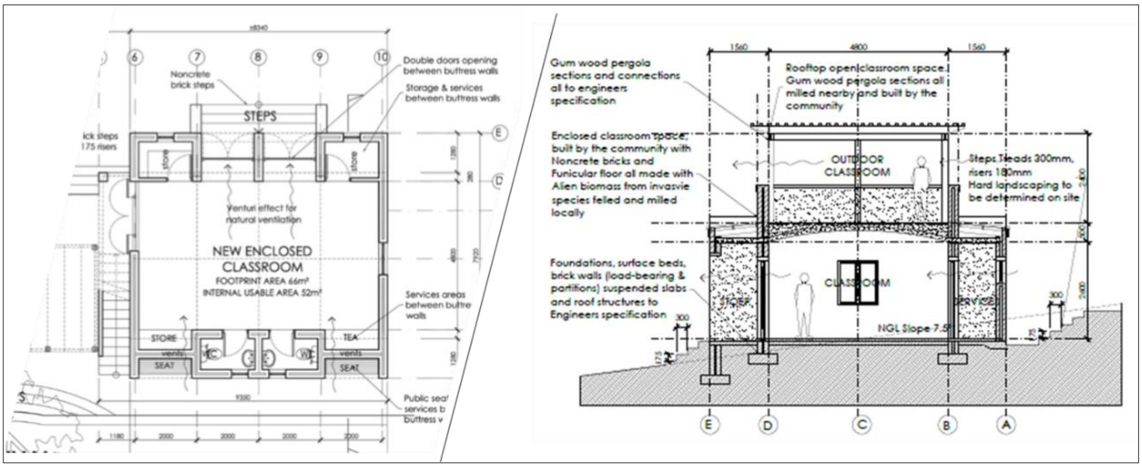

Figure 6. Plan and section of creche building.

2.7. Life Cycle Assessment

In conventional buildings, floors slabs are recognised as the item with the largest GWP due to their material intensiveness and structural inefficiency . For this reason, the partial life cycle assessment (LCA) presented here focuses solely on the GHG emissions related to the funicular floors' production and construction (stages A1-A3), transportation (A4) and disposal (C1-C4) and it highlights the savings compared to a business-as-usual approach, in this case a 200 mm thick RC flat slab throughout.

2.8. LCA Stages A1-A3 and A4-A5

A bill of quantities for the crèche indicates that, by using the negative ECC stated previously, ca. -1,840kgCO_2eq are stored in the whole 40 m^2 of funicular floor. These offset the positive emissions linked with the regular concrete and rebar present in the edge beams, which amount to around 1,140 kgCO_2eq, using average ECC values from .

Regarding Stage A4, only the funicular floor sections were prefabricated in Cape Town and transported to the site, resulting in 210 kgCO_2eq of transport-related emissions. All other materials are sourced within a 15 km radius from the crèche and processed directly on site and the contribution of the limited transport distances is deemed negligible.

Regarding the construction stage A5, the assembly and completion on site is a largely manual process requiring only a small crane for lifting the panels at height. The precast vaulted shells act both as structure and as lost formwork for the filler mix, meaning that neither falsework is transported back and forth from a site nor waste is generated in the construction process.

As a result, the entire GWP of the floor during stages A1 to A4 amounts to -490 kgCO_2eq permanently stored in the building, equivalent to a remarkable -8 kgCO_2eq/m^2. If the crèche had been built conventionally with a 220 mm thick flat reinforced concrete slab, its GWP would have been in the order of 5,120 kgCO_2eq, equivalent to 80 kgCO_2eq/m^2.

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2.9. LCA Stages B1-B7

Evaluating the impact of the good thermal properties of the low-density brick cavity walls is beyond the scope of the present paper but is deemed highly favourable in comparison with conventional hollow concrete blocks, especially when used in double-leaf cavity walls.

Regarding the usage stage though, the environmental benefits of NC adoption extend well beyond direct GHG emissions and explain the country's investments for the eradication of IAPs, estimated in a startling 320 million Euros annually : IAPs regularly burn in wildfires, as do other species, however, the IAPs burn hotter and release more carbon than indigenous vegetation ; by removing them, both the potential emissions associated with future wildfires as well as those associated with the current practice of burning the biomass, are avoided. In addition, while IAPs may absorb more CO_2 than the slow-growing native *fynbos*, the latter take up much less water, hence restoring the natural water table .

2.10. LCA Stages C1-C4 and D

Here only a qualitative evaluation is done. In first approximation, the mechanical energy to crush the NC mixes is significantly lower than for RC, due to the limited mechanical strength of the mixes and to the complete absence of any embedded reinforcement.

Regarding Stage D, it has been established through testing that NC elements can be crushed and remixed into new components without deterioration of mechanical properties. These important findings in terms of circularity will be published separately.

3. Results and Discussion

3.1. Structural Performance

The load-bearing capacity of the NC funicular floor modules and of the NC brick walls was tested under real-world conditions to ensure they meet the highest engineering standards. Particularly, the proven structural integrity during and after long fire exposures positions NC products as the go-to solution for low cost, low carbon yet safe and dignified settlements in South Africa, where fires commonly have devastating consequences on people and buildings.

3.2. Environmental Impact

The NC mixes drastically reduce greenhouse gas emissions compared to traditional concrete and blockwork. The use of renewable and locally sourced invasive plant biomass not only leads to carbon negative building elements but also aids in the management and eradication of these species, providing a number of ecological benefits, such as restoration of the indigenous flora, replenishment of the water table and risk-reduction of wildfires.

3.3. Socio-Economic Impact

Income inequality in South Africa is the highest in the world and unemployment is rife at 32%. Building affordable, dignified and resilient housing at scale using NC products and technologies has the potential to create exactly the type of low-skill, labour-intensive jobs needed to bring these numbers down. Since the wider aim of the project is also to create new local job opportunities, people are currently being trained to remove IAPs, prepare the biomass mixes, produce the bricks, cast and install the prefabricated floors and then finish them in-situ with the non-structural filler on site. This process thus creates at least five new entry-level potential job descriptions.

The R&D phase and the offsite manufacturing of the floor panels for the Elandskloof crèche has already created business for the local OneNil Construction team of seven (see **Figure 7**), who are using their newly acquired knowledge to explore other building components. They are also tasked to pass on their skills to local communities, training them to collect and process the biomass, to produce bricks and to cast the floors locally in the provided moulds, as well as to assemble all components on the building site.

Figure 7. The local OneNil Construction team (led by Mr Grabeth Nduna, lhs) enjoying the hands-on experience casting shells.

4. Conclusion

This paper demonstrates the feasibility and benefits of using *nonCrete* materials and products for low carbon, low cost buildings in South Africa: the innovative material reduces greenhouse gases, preserves resources, and promotes environmental sustainability through the creation of 'green' jobs. When optimally designed and implemented, NC products meet all engineering standards and create robust, elegant and resilient developments.

The case study successfully exemplifies a circular economy: biomass waste from felled IAPs is diverted from landfill, where decomposition or burning would emit greenhouse gases, its biogenic carbon is permanently stored (also after demolition) and the natural ecosystem is regenerated as IAPs are replaced with indigenous flora, restoring the natural water system.

The Elandskloof créche – built by locals using *nonCrete* biomass materials – aims to serve as a beacon of hope and potential, allowing the community to test the material and clear the alien invasives, opening up land for agriculture and biodiversity restoration. The project not only delivers a safe community hub for the children but also provides the adults with an opportunity to learn new skills.

4.1. Outlook

The findings of this study pave the way for broader adoption of sustainable construction practices, contributing to the global efforts to combat climate change and promote greener building methodologies. The construction of the crèche, with the active involvement of the local community, plays an important role in upskilling community workforce, enabling them to use the construction techniques for building their own homes that are resilient and eco-friendly, setting an example for other communities in South Africa to follow.

It is the intention of the *nonCrete* designers to facilitate the broad uptake of the material and method (within the informal housing sector in particular), removing licencing barriers where possible, without compromising quality control.

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