EFFICIENCY OF HIGH PERFORMANCE CONCRETE TYPES INCORPORATING BIO-MATERIALS LIKE RICE HUSK ASHES, CASSAVA STARCH, LIGNOSULFONATE, AND SISAL FIBRES

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Abstract

Over the last decades concrete has evolved from a simple mass construction material towards a sophisticated multi-component system. The design parameters for the mixture composition of concrete have significantly increased from strength based towards overall or specific performance based. As a result the variety of concrete has increased yielding a number of special concrete technologies such as Self-Compacting Concrete (SCC), High-Performance Concrete (HPC), Strain Hardening Cement Based Composites (SHCC), and many others. Due to their complex mixture compositions and a multitude of possible interactions between constituents, these concrete types are preferably composed of special components like well-defined powders and sophisticated chemical admixtures. This makes such concrete technology expensive and limits their application to regions with the required material supply chains. The paper puts focus on materials, which are less well studied in conjunction with high performance concrete, but which are available in many developing countries, and in particular sub-Saharan Africa. The paper shows how SCC can be designed without polycarboxylate ether superplasticizer and well defined fillers, but with lignosulphonate, cassava starch and rice husk ash. The positive effect of well processed rice husk ashes is demonstrated. Furthermore results are presented of SHCC where typical components like polyvinyl alcohol fibres and fluy ash are replaced by sisal fibres and limestone filler, respectively. The results point out that high performance concrete applications do not have to be limited to a boundary framework with availability of well-defined raw material supply structures and sophisticated admixtures or fibres. Concepts are presented how innovative concrete technologies can be developed based on indigenous materials.

Keywords:

Rice husk ash, Sisal fibres, Lignosulphonate, Cassava starch, High performance concrete

1 INTRODUCTION

During the last three decades concrete has emerged from a rather simple mass construction material based on three basic components, i.e. cement, water, and aggregates, into a high performance material, which can be adjusted according to high performance applications and ultimate user specifications. The reason for the rapid evolution was the increasing awareness of how to benefit from mineral additions and chemical admixtures. Both can be considered as the most influential factors, which yielded a boost of technology from the early beginnings of the1980s.

The range of consistencies previously applied on construction sites was limited. The mechanical properties of cementitious systems were depending upon the water-cement ratio, but a relatively high water content was required in order to provide workability. This indicates a close relation between consistencies and mechanical properties. However, with the invention of plasticizers and the further evolution of superplasticizer technologies along with more innovative mixture compositions, the situation has since been modified. The incorporation of superplasticizers into concrete mixture composition eventually facilitated concrete engineers to improve the workability properties without a need to increase the water-cement-ratio (w/c) or to significantly reduce the w/c, which finally resulted in concrete with higher performance and specified properties (Schmidt et al., 2013d, Schmidt et al., 2013e). Concrete has emerged from a simple three-component system into a complicated multi-component system, and along with the new composition tools, comes the complex considerations concerning optimisation of mixtures with regard to specific performance requirements.

Today, concrete engineers can vary consistencies between very stiff and self-compacting concrete (SCC). The possibility to tailor rheological properties of concrete finally opened up the gates to multiple new technologies, where design criteria is no longer limited to the Young's modulus and the compressive strength, but often comprises different aspects such as durability, ductility, flowability, fire resistance, and other concrete necessities.

Therefore, it is concluded that the capability to control the rheology of concrete systems can be considered as the catalyst for concrete innovations such as polymer modified cementitious composites (PCC) SCC, high-performance concrete (HPC), ultra-high performance concrete (UHPC) or strain hardening cement based composites (SHCC).

These novel technologies provide enormous innovation potentials in concrete constructions and in the field of strengthening and repair of structures for various constructions worldwide. However, the adequate established materials typically depend upon sophisticated and expensive constituents that are not always available everywhere in the world. In most countries that look back upon centuries of elaborate concrete construction, the use of fly ash (FA), ground granulated blast furnace slag (GGBS), or micro silica is well established. The integration of these materials into cement and concrete technology went hand in hand with the respective industries, such as steel and deep coal processing. For example in sub-Saharan Africa (SSA), these industries are scarce. The use of FA is very uncommon in most African countries except South Africa. The same applies for construction chemicals and fibres. For modern HPC types, superplasticizers based on polycarboxylate ether (PCE) are typically used. Typical fibre types are based on steel, polypropylene (PP), or polyvinyl alcohol (PVA). While the supply infrastructure in most countries in Europe, East Asia, and Northern America are well functioning. SSA is mainly supplied by South Africa and the Arabian Peninsula; more recently supply chains are also being established in East and West Africa. However, the range of available agents is limited and the transportation costs are primarily economically feasible for special applications.

The availability or financial feasibility of established sophisticated materials for HPC is clearly limited in SSA despite its significant use for the development of infrastructure, housing and maintenance projects. Hence, it is more beneficial to look at indigenous materials available in the local markets that can help facilitate the implementation of HPC.

This paper considers the application examples of SCC and SHCC through a selection of bio based materials. The discussion focuses on implementing cheaper and locally available materials; yet functioning, as an alternative to sophisticated mixture constituents.

2 RICE HUSK ASH AS SCM OR CONCRETE ADDITION

2.1 SSA cement and concrete market needs

The cement and concrete market in SSA is rising, nevertheless the prices of cement are still exceptionally high. The price of cement for 50 kg bag ranges from USD 8 – 25 in most countries in SSA, which is very expensive for an extensive use in normal construction projects (Msinjili & Schmidt, 2014). Labour costs are significantly lower in African countries than in European countries, whereby cement is reasonably cheap, while the personnel costs are the major economic factor of concern. However, despite the high cement prices, in most countries in SSA, ordinary Portland cement (OPC) is still the most widely used cement type. CEM II types typically blended with limestone filler and occasionally pozzolana cement types are also available in the market, but are exceptionally limited. Hence, it is quite obvious that cement replacement offers an enormous potential to reduce the local cement costs, e.g. by making use of the natural pozzolana or calcining natural clays as well as valorising agricultural by-products that are available all over the continent.

Agriculture is one of the leading economic sectors in most countries in SSA. Linking agriculture with civil engineering would be beneficial considering that most agricultural by-products not only possess an eco-friendly characteristic but also have cementitious tendencies. Such tendencies occur after an adequate tempering process and offer the possibility to be used as supplementary cementitious materials. Examples of such agricultural by-products are rice husk ash (RHA) or bagasse ash.

Unfortunately, these are not yet extensively utilised in the construction industry for reasons that may result from the lack of knowledge of the material's characteristics when blended with cement or used in concrete production. SSA produces approximately 20 million tonnes of rice annually (FAOSTAT, 2010). The top leading rice producers in SSA are Nigeria, followed by Mali, Guinea and Tanzania. From the production, 30% of dried paddy rice is made up of husks and generally treated as a waste material. Tanzania produces ca. 1.1 million tonnes of rice and is the leading rice producer in Eastern Africa. This estimates to over 300,000 tonnes classified as "wastes", which are disposed by burning because of its negligible protein content, hence cannot be used for livestock feeding (Mhilu, 2014).

Fig. 1: Burning of RHA in Tanzania.

2.2 RHA as cement replacement

To date, RHA is typically calcined without an established tailored process for use as a mineral binder component (Fig. 1). Nevetheless, at proper incineration conditions RHA is found to contain 85% – 95% amorphous silica with high pozzolanic properties suitable for high quality cement replacement. Addition of high quality RHA in cement and concrete not only increases the mechanical properties but also increases the micro-structural density, which makes concrete more durable (Krishna, 2012). Production of the ash is crucial to obtain good quality products. To produce a low carbon-content with loss on ignition (LOI) of less than 4% and high pozzolanic properties, the following incineration conditions should be maintained:

- Temperatures not exceeding 650°C with constant air access
- Duration of burning to be between 20 and ca. 30 minutes
- Natural cooling of the burnt ash for a minimum of 24 hours in a dry area immediately after burning is necessary.

Preliminary tests were conducted at BAM laboratories to investigate the chemical and mechanical properties of properly calcined RHA. Rice husks collected from Tanzania were incinerated in a kiln in Germany at a maximum temperature of 650°C for 25 minutes, and heating rate of 100°C per hour followed by natural cooling. Manmade kilns are also feasible for production of the ash as long as the environmental conditions can be controlled in a reproducible way.

The RHA was ground to a maximum grain size of 1 μm and used as a replacement of OPC at percentages of 10, 15, 25 and 30 by volume for production of mortar specimens. Fig. 2 shows that the compression strength tests produced results higher than the control (i.e. 0% replacement). The highest compression strength at 7 days occurred with 25% replacement, whereas tests for 28 days showed compression strength results much higher than the control at 20% and 30% replacement.

It is researched that replacement of OPC with RHA exhibits a high early strength and can produce a long-term strength development producing a compressive strength higher than the reference OPC mix.

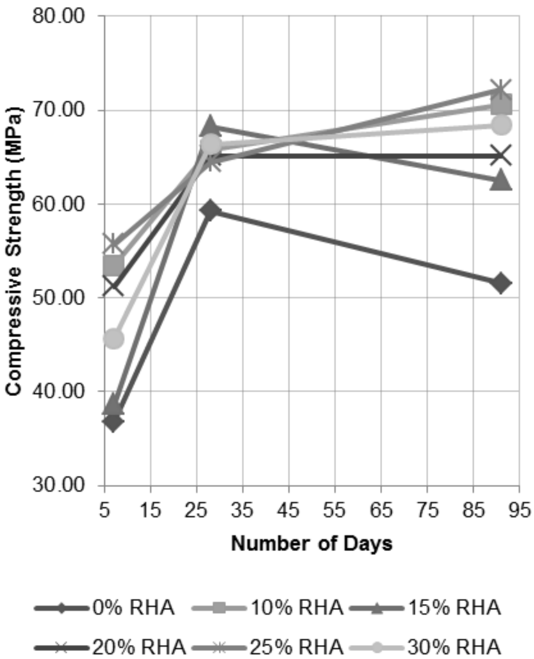

Fig. 2: Activity index of mortar at different cement replacement ratios with RHA.

3 SELF COMPACTING CONCRETE BASED ON LIGNOSULPHONATE, CASSAVA STARCH AND NATURAL POZZOLANA

As demonstrated in section 2 of this paper, it is possible to develop mineral binder concepts with high OPC replacement rates based on locally available resources without resorting to classical and limited materials such as FA or GGBS.

However, high performance concrete types are typically composed of a variety of important supplementary constituents beyond the binder material. For self-compacting concrete for example it is of highest importance to adjust the flow properties adequately by increasing the powder volume as well as by adjusting the yield stress and plastic viscosity by use of superplasticizers and stabilising agents.

3.1 State of the art

The boundary framework for casting of concrete in most sub-Saharan countries clearly distinguishes from the situation that can be found in many industrial countries. This situation has to be considered in order to develop tailored concrete concepts. In addition to the high cement prices, further aspects detrimentally affect the casting of concrete for optimal performance:

- Sand, aggregates, and bags of cement are stored on the construction site, sometimes with some type of shelter, but often exposed to the elements. Thus the materials' surface properties and water demands may vary greatly during daily production.
- Water is often added to mixes using optical or haptic consistency assessments, which causes scatter of the w/c ratio from batch to batch.
- Mix designs are typically implemented based on the dry granular bulk density. Since the pouring properties of powders and aggregates can differ greatly, the volumetric composition of fresh concretes can vary widely.
- Concrete mixing machines are often hired for a specific period rather than owned due to financial constraints. More commonly, labourers mix concrete manually on-site using shovels, causing a large scatter in dispersion qualities.
- Compaction tools are not generally adequate for optimum compaction. Pokers are often used and compaction by tamping is common.
- Supply chains are not always optimised for rapid processing and are often unsteady. For high-rise buildings, concrete needs to be mixed on the ground floor and transported by wheelbarrow to each successive floor. The period between mixing and placing thus increases with every newly constructed storey. Additionally, fresh concrete is often stored after mixing until a sufficient number of batches have been assembled, before being transported to the final casting place; typically done manually in buckets (Fig. 3).
- Construction site staff are usually hired on demand and remunerated daily. They are generally not trained and lack awareness of the significance of w/c ratio, proper compaction or curing. This is critical, since water finally is the only option to modify the fresh concrete's properties.

Fig. 3: Interim storage site for the collection of several concrete mixing batches.

3.2 Flowable concrete in order to overcome casting problems

The previously listed factors do not inevitably create poor concrete quality. However, they impose a high risk on inconsistencies in the quality over the entirety of all processes. Regardless of the fulfilment of the structural requirements on the minimum strength, unsteady mechanical properties within the same or neighbouring concrete components can exhibit a negative impact on the durability and induce internal stresses and cracks.

Although SCC is typically considered to be a complicated technology, it can be an adequate solution in order to overcome the negative influencing parameters mentioned previously, by uncoupling the concrete quality from influences induced by the equipment, staff and supply situation. A similar idea actually triggered the invention of SCC in the 1980s in Japan. Scientists observed a correlation between decreasing labour skills and declining structural durability (Nagataki, 1998, Ozawa et al., 1989) and invented SCC with the aim to create a highly durable concrete quality, which was independent of the skill level of the labourers.

A major obstacle for the use of SCC in most countries is the typical higher costs influenced by the high powder content as well as the chemical admixtures. Therefore, reasonable SCC concepts for SSA should potentially be produced relatively at lower price than normal concrete. Due to the high costs of cement that can be found everywhere in SSA, concrete process can be significantly be reduced by lowering the cement content and applying a reasonable particle packing design that absorbs the negative effects of the lower cement content. The reduced cement volume can be replaced by locally available materials such as natural pozzolana or properly calcined RHA as previously elaborated.

However, the major price driving factor for SCC is the superplasticizer, typically PCE, which is relatively more expensive in SSA due to the transportation requirement. Since its invention in the 1980s, SCC has quite evolved and today there are plenty of different mixture composition approaches and philosophies. If the aim is not to achieve the highest possible compressive strength, mixture concepts with moderately high water contents are a realistic option to maintain a long lasting flow performance and helps reduce the superplasticizer demand (Schmidt et al., 2014a). This also helps to enhance the casting of concrete at high temperatures. Due to its accelerating effect on hydration, hot climatic conditions cause rapid loss of workability (Schmidt et al., 2014b, Schmidt, 2014). Rapid workability loss is disadvantageous for SSA construction sites characterised by unsteady casting logistics from lack of equipment such as pumps and machinery. The major influencing factors of flowable concrete that determine the flow retention are the water to powder ratio (w/p) and the charge density of the superplasticizer (Schmidt et al., 2014b, Schmidt, 2014). As illustrated in Fig. 3, low w/p mixtures stiffen too rapidly due to rapidly occurring morphological changes on the surfaces that cause lesser mobility of particles among each other (Schmidt et al., 2013c). Therefore, SCC optimised for hot weather conditions should not be designed for ultimately low w/p values (w/p ratios between 0.5 and 0.65 might be realistic) (Schmidt, 2014).

The superplasticizer then does not inevitably have to be based on polycarboxylate but can also be based on lignosulphonate (LS). LS is less versatile than PCE and less efficient in operating at lowest possible water volumes, but it shows a reasonable yield stress reducing effect, particularly in conjunction with a moderately high water content. As a waste product from cellulose industry it is largely available all over SSA and it can be purchased at a reasonably low price. However, mixture compositions with higher water contents may require an additional stabilising component. Reasonable solutions for bio-based stabilising agents are starches based on cassava - also available in many African countries. The starch of cassava is comparable to potato starch, which if modified is already an established stabilising agent for concrete (Schmidt et al., 2013a). Tab. 1 provides an overview of typically used mixture constituents for SCC technology compared to alternative materials that are promising for use in SSA.

3.3 Application of SCC as pre-mixed dry compound

Tab. 1 provides examples of mixture constituents that can potentially be used for SCC. Nevertheless it has to be verified that SCC can function optimally without sophisticated and well defined materials. In order to avoid negative influences during the mixing process, it was proposed to apply SCC in form of a pre-mixed binder compound already incorporating chemical admixtures, cement, filler. and sand, that can be delivered to construction sites in pre-mixed bags.

Tab. 1: Alternative materials available in SSA.

Constituent	Typically used in SCC	Alternative materials in SSA
SCM	Limestone filler, ground granulated blast furnace slag, fly ash	Natural pozzolans, limestone filler, rice-husk ash, bagasse ash
Fillers	Silica fume, limestone filler, fly ash	Natural pozzolans, limestone filler, rice-husk ash, bagasse ash
Super plasticizer	Polycarboxylate ethers	Lignosulphonates, naphthalene sulphonates
Stabilising agent	Cellulose ethers, potato starch, sphingan gums	Cassava, maize, or potato starch, cellulose

Such a compound only needs to be amended by water and local aggregates on site (Schmidt et al., 2013b).

Based on a four step optimisation procedure, the details of which have been published (Schmidt et al., 2015), a SCC compound was developed with the aim to at least reach the performance of a reference real application concrete but at a very flowable consistency. The optimisation steps were as following:

- Optimising the particle packing density by experimentally determining the optimum ratio of cement and fillers
- Identifying the minimum binder paste volume in mortar
- Identifying the optimum adjustment of superplasticizer, stabilising agent and water for best achievable rheology
- Stepwise increase of coarse aggregates in order to find the threshold mortar content below which the flow properties are poor.

The final mixture composition can be found in Tab. 2. The reference concrete for comparison with the SCC compound was a normal-consistency concrete with a cement content of 418 kg/m³ and a w/c of 0.48. The 28-day tender compressive strength was ±25 MPa, however, the structural design was based on a 20 MPa compressive strength in order to cater for performance scatter during the entire construction progress. Drilled cores from the reference concrete provided a cylinder compressive strength in the order of magnitude of 16 to 18 MPa.

One hour after mixing, the slump flow of the SCC was 635 mm (Fig. 4). The strengths after 28 and 90 days were 56.2 MPa and 68.4 MPa, respectively. The strength increase after 28 days clearly indicates the pozzolanic activity of the natural pozzolana used. These values are significantly better than those of the reference mix. The cement content in the final compound composition is still very high, yet lower than in the reference mixture. The higher strength properties of the compound mixture compared to the reference mixtures (Fig. 5) indicates that a supplementary prominent cement reduction can be achieved without falling below the reference values. Future investigations will focus on how much cement can be replaced by limestone filler or other fillers to save cement costs.

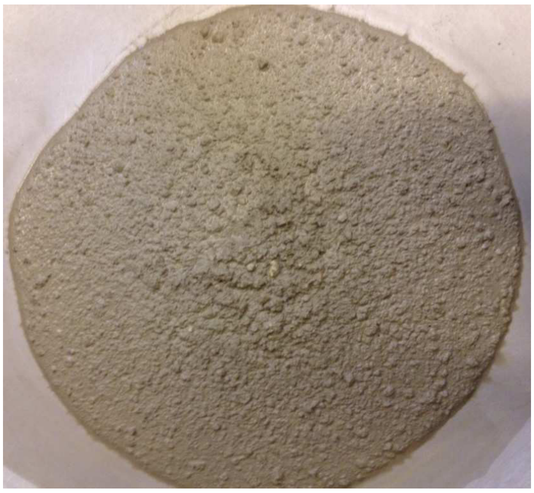

Fig. 4: SCC made with natural pozzolana, lignosulphonate SP and cassava starch based stabilising agent.

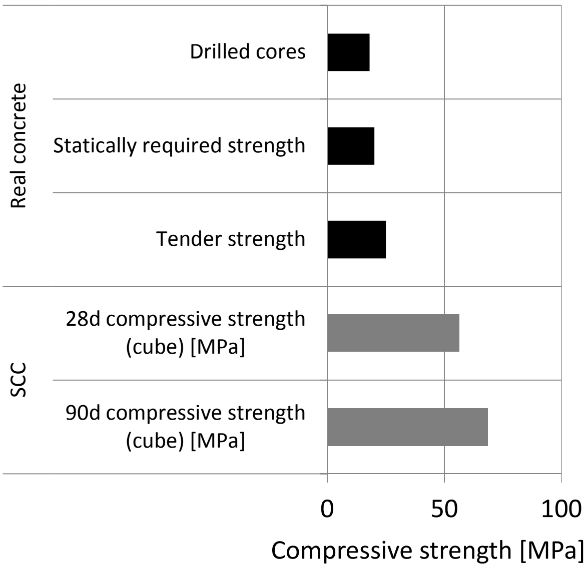

Fig. 5: SCC made with natural pozzolana, lignosulphonate SP and cassava starch based stabilising agent.

Tab. 2: Alternative materials available in SSA.

	Component	[kg/m³]
Pre-mixed compound	OPC	399
	Natural pozzolana (from Uganda)	80
	Fine sand [0 -2 mm]	972
	Lignosulphonate SP (Powder)	7.8
	De-foaming agent	0.02
	Cassava starch (from Nigeria)	3.0
Construction site addition	Water	238
	Aggregate [2 – 16 mm]	613

4 USE OF SISAL FIBRES TO IMPROVE THE POST CRACK MECHANICAL BEHAVIOUR

4.1 Benefits of highly ductile concrete

The sub-Saharan African environment can be challenging to structures. East and Southern Africa is considered to be an earthquake zone. A technology that is considered to be promising for the repair and strengthening of structures exposed to dynamic loading are so called strain hardening cement based composites (SHCC), which show a highly ductile structural performance.

This performance is achieved by the use of short polymeric fibres. The mode of operation of this kind of concrete is based on multiple crack formation. After the occurrence of an initial crack, the fibres are activated and take over the forces with the result that the next crack will occur in a different location, where again a fibre activation takes place (Paul and van Zijl, 2013). By this effect under bending or tensile forces multiple finely distributed cracks are formed without significant crack opening width. As a result the concrete can maintain its load level or take supplementary loads after the formation of the first crack while the strain is significantly larger than in normal concrete (which would rupture instantly as soon as the crack opening width exceeds a critical level).

It is obvious that the adjustment of the fibre and the mechanical properties of the binder paste have a strong influence on the structural performance of such concrete. In order to achieve high ductility, high strength is not the major aim. Mixture compositions therefore typically contain high water-cement ratios and high amounts of finest micron sized materials with maximum grain sizes below a few millimetres. Most commonly high amounts of fly ash are incorporated into the mixture compositions. The optimum performance can be achieved by adding PVA fibres into the mix in the order of magnitude of 1.0 to 2.0 % by volume. However, strain-hardening performance is also possible with steel and polypropylene fibres in a similar volumetric ratio.

4.2 SHCC incorporating sisal fibres

The aforementioned fibre types are extremely expensive and not easily available everywhere in SSA. However, SSA offers a number of bio-based fibre types obtained from agricultural by-products e.g. sisal fibres. Sisal is primarily in large production in East Africa in countries such as Tanzania and Kenya.

Therefore it was aimed at analysing whether sisal fibres can replace the expensive and difficult to purchase PVA fibres. Due to the lack of fly ashes in most countries in SSA it was furthermore aimed at replacing the fly ash by limestone filler, which is much easier available. In order to avoid high prices induced by finest powders, the maximum grain size was 2 mm. The mixture composition of the investigated SHCC is shown in Table 3.

Fibre contents were varied between 0.80%, 1.25%, and 1.75% by volume. Besides sisal fibres for comparison reasons steel fibres, viscose fibres and PVA fibres were observed in the same volumetric ratios.

Tab. 3: Alternative materials available in SSA.

Component	[kg/m³]
OPC	270
Limestone filler	791
Water	305
Sand [2 mm]	687

4.3 Effect of amount of sisal fibres

Fig. 6 shows the influence of the amount of sisal fibres on the post tension structural behaviour in comparison to a reference mixture without fibres in a three point bending flexural test setup for mortar prisms (40 mm x 40 mm x 160 mm).

While the stress level for the mortars without fibres is higher than with fibres, the component immediately fails after achieving the crack load. For fibre reinforced mortar types a loss of the bearable stresses can be observed, however, with a significant post cracking behaviour. It can also be observed that increasing fibre dosages improve the strain levels that can be achieve. At a fibre dosage of 1.75% by volume the stress decrease after the crack is marginal and significant further deformations can be absorbed without stress decrease. The results show that the sisal fibres significantly increase the ductility of the investigated mortars. Assuming a similar trend for the fibre content, it is likely that higher dosages of sisal fibres can create a pronounced strain hardening behaviour.

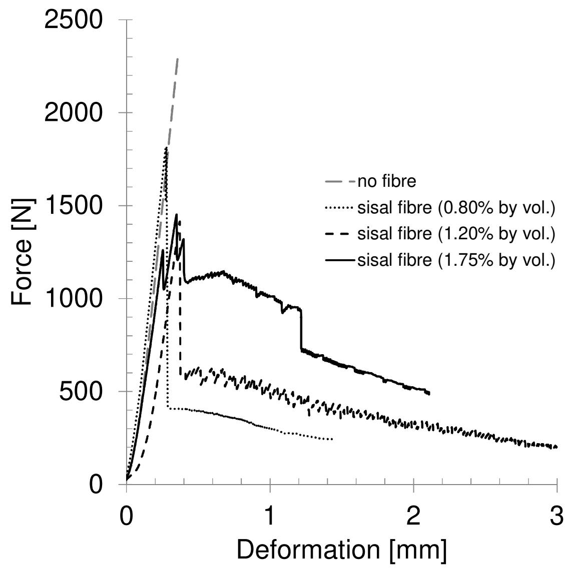

Fig. 6: Influence of the fibre content on the post crack behaviour of SHCC mixtures containing sisal fibres (cement content = 270 kg/m³, w/c = 1.13).

4.4 Sisal fibres in comparison with other fibre types

Fig. 7 shows the load-deformation curves for different fibre types at a dosage of 1.75% by volume. Due to the high tensile strength and the small diameter the PVA fibre shows outstanding behaviour compared to all other investigated types with a clear strain hardening post crack behaviour. Steel fibres and sisal fibres show similar post crack behaviour, however, the steel fibre specimens show slightly higher stresses and strain at crack occurrence. It is assumed that the post crack behaviour can be improved and a strain hardening behaviour can be achieved with finer sisal fibres, even if the tensile strength of sisal fibres is low compared to the tensile strength of steel or PVA fibres. The least significant post crack behaviour can be observed for the viscose fibre.

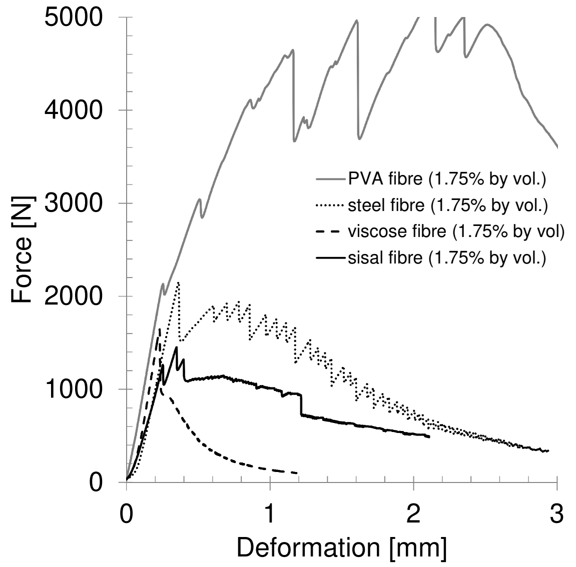

Fig. 7: Influence of the fibre type on the strain hardening post crack behaviour at a fibre content of 1.75% by vol. (cement content = 270 kg/m³, w/c = 1.13).

5 CONCLUSIONS

The paper discussed the use of a variety of different bio-based materials that can be used for high performance concrete types. The focus of the observation was put on raw materials that can be found in sub-Saharan Africa for the reason that on the African continent the valorisation of agricultural by-products and wastes is supposed to be a promising approach to develop novel and sustainable concrete.

The use of burnt rice husk ash (RHA) as either supplementary cementitious material or as a filler in concrete was discussed and experimental results were presented that show the high pozzolanic activity of such material

Self-compacting concrete (SCC) was shown to be a promising technology to overcome drawbacks in the supply and processing chains for concrete casting. In order to apply SCC economically and environmentally efficiently a conceptual mixture composition was presented based on lignosulphonate (LS) and cassava starch as chemical admixtures and on natural pozzolana as filler component. The concrete outperformed a non-flowable reference concrete significantly and provides a huge potential for further reduction of the cement content.

Finally the use of sisal fibres as a replacement of expensive polyvinyl alcohol (PVA) fibres in strain hardening cement based composite (SHCC) was discussed. The present results have shown that the sisal fibres cannot perform in a similar way as the PVA fibres, but nevertheless can significantly increase the ductility and post cracking behaviour of the concrete.

Further research is needed to exploit the full potential of sisal fibres by optimizing the fibre geometry and fibre content.

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