Bachelor's thesis

Runa Aaland Eggum
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# Bio-based materials for sustainable concrete

## A review on application of bio-based materials in enhancing sustainability of concrete industry

**May 2020**

**NTNU**
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Sammendrag: Denne oppgaven omhandler hvordan biobaserte materialer kan redusere $CO_2$-avtrykket for betongindustrien. Den pågående globale oppvarmingen må bremses ved at $CO_2$-utslippene reduseres. Betongindustrien er i dag en betydelig utslippsaktør og det må derfor iverksettes tiltak i industrien. Oppgaven gir en oversikt over aktuell forskning på temaet og skal svare ut problemstillingen «Hvordan kan biobaserte materialer bidra til en mer bærekraftig betong?» De aktuelle materialene som er presentert gjennom oppgaven bidrar til bærekraft gjennom å redusere bruk av klinkersement, forlenge konstruksjonslevetiden og ved at de biobaserte alternativene kan erstatte materialer som ikke er biologisk nedbrytbare. Videre blir miljøpåvirkninger, påvirkninger av betongens egenskaper og mulige bruksområder for alternativene diskutert og anbefalinger for videre arbeid og forskning blir presentert. Problemstillingen blir besvart gjennom en litteraturstudie der et bredt utvalg av aktuell forskning på området er sammenstilt og sammenlignet. Resultatene viser at det både er muligheter, gevinster og utfordringer ved å nyttiggjøre seg av biobaserte materialer i betong. Naturlig fiberarmering gir forbedret styrke for enkelte naturfiber, men bruk kan bidra til utfordringer knyttet til både støpelighet og holdbarhet. Videre er det funnet alternative bindemiddel og tilsetningsstoff som forbedrer både styrke, holdbarhet og andre egenskaper i betong. Det er avdekket biobaserte tilslag som kan anvendes for enkelte bruksområder og bruk av selvhelbredende betong kan potensielt forlenge konstruksjonslevetiden. Det er utfordringer ved å endre den ordinære betongsammensetningen og videre forskning og utredninger må gjennomføres før de kan anvendes i ordinær betongproduksjon. Det er likevel avdekket ulike bruksområder for alternativ materialbruk og at det er et potensial for å produsere bærekraftig betong i fremtiden. Utarbeidelse av felles standarder for videreutvikling og testing av alternative material framstår som avgjørende for å øke kvaliteten på framtidig forskning.

Stikkord:

| | |
|---|---|
| Bio-based materials | Durability |
| Sustainable concrete | Environment |

| Runa Aaland Eggum | Inger Enes Gjerde | Linn Olberg Lundwall |
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# Foreword

The work presented in this thesis is as a part of the bachelor’s degree programme in Civil Engineering carried out in the department of Manufacturing and Civil Engineering at the Norwegian University of Science and Technology.

The construction industry is responsible for more than 30 % of the world`s greenhouse gas emissions. As Structural Engineering students we have gotten equipment to seek alternatives for the construction industry to build for the future. Based on this we have taken interest in exploring bio-based materials that may mitigate the impact of one of the most environmental unfriendly construction materials - concrete. The results of this study will facilitate a better understanding of the effect of bio-based materials in concrete and should serve as the basis for further research and applications.

We want to thank our supervisor professor Mohammad Hajmohammadian Baghban, who has given us guidance. Thank you for being available, always engaged and professionally updated.

The thesis was carried out during the spring 2020, the start-up of COVID-19 State of Emergency. Although life presented additional challenges in this period, we are proud to present our work as a result of experience and knowledge.

May 2020

Runa Aaland Eggum, Inger Enes Gjerde and Linn Olberg Lundwall

# Abstract

This paper considers how $CO_2$ emissions related to the concrete industry can be reduced by using bio-based materials in the production. Cutting emissions is crucial to slow down global warming, and as the concrete industry is a sizeable contributor to current emissions, action must be taken now. This paper presents an overview or a “state-of-the-art” of current research on the area, answering the research question “*How can we use bio-based materials to get more sustainable concrete*?”. The main solutions reviewed in this paper are alternatives and methods to reduce the amount of clinker cement, achieve extended longevity in structures and finding bio-based alternatives to non-biodegradable materials. The impact of these solutions on the environment, the properties of the concrete and the possible applications are discussed, and further action and areas of research is recommended. The research question is answered through a literature review, compiling and comparing results from a wide selection of current research on the area. The results implicate that there is a range of possibilities, gains and challenges when it comes to bio-based materials in concrete. Natural fibre reinforcement gives improved strength for some fibres but presents workability and durability issues. There are several additives, admixtures, binders and fillers that improve both strength and durability as well as other properties of the concrete. Bio-aggregates can be utilized for some applications and different self-healing mechanisms can extend service life of structures. All the materials have some challenges related to them, as well as areas where more research must be conducted before they can safely be utilized in concrete production. However, the majority of the materials reviewed have a variety of different applications and show great potential for making more sustainable concrete. Creating common approaches and standard testing conditions for these kinds of materials is crucial to the quality of further research.

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# 1 Introduction

Concrete is by far the most popular building material in the world, and an enormous amount of concrete is used worldwide. As a building material it is durable, easily prepared, can be fabricated into different shapes and has a wide range of applications. Thermal heavy constructions as concrete constructions also can serve as a heat reservoir and offers soundproofing properties. In addition, concrete is a material that provides good fire resistance. Although concrete has these advantages as a building material it is known that the production of cement is one of the biggest sources of carbon dioxide emissions. Cement is responsible for about 7 % of global man-made $CO_2$ emissions. The International Energy Agency (IEA) are expecting an increase by 4 % globally in their "Reference Technology Scenario (RTS2)" by 2050 (IEA, 2018).

Cement is produced through crushing and burning limestone along with smaller amounts of quartz, iron oxide and alumina.

During the production, $CO_2$ is released in two ways. The first is in heating the kiln by burning fossil fuels, which is responsible for about 40 % of the emissions. The second is the following chemical reaction when calcium carbonate is thermally decomposed and produces clinker, the main material in cement, and liberates $CO_2$, responsible for about 50 % of the emissions.

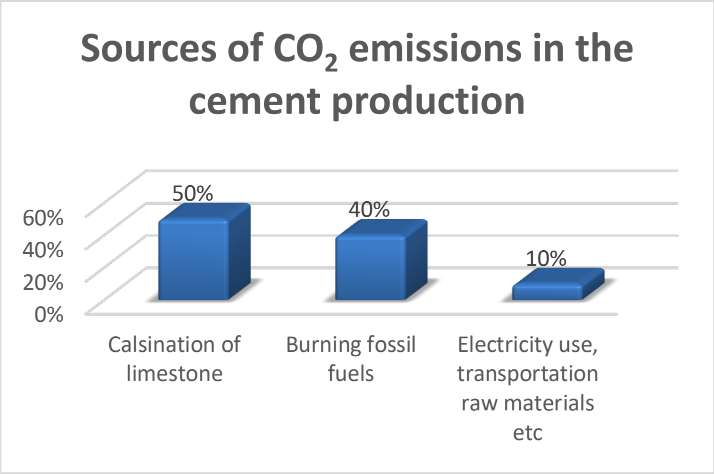


*Figure 1 Emission sources*

The awareness on the environmental impact of cement production demands that we search alternatives and transform the production to reduce its carbon footprint. Concrete is far too useful as a building material that we can replace it. Nevertheless, the society need to explore how the industry can mitigate the effects of climate change. There has been a lot of development in recent years and it is continually developing. Concrete is getting smarter and can self-repair. Concrete is being made stronger and offer material efficiency and we use substitutes that demands less cement in the mix and reduce its carbon footprint. Recently, we also have been seeking solutions to solve environmental problems unrelated to the concrete industry and concrete is for instance been used to store agricultural waste by incorporating them into the concrete mix. Concrete also absorbs some of its carbon emissions during and at end of life and it is an ongoing technology development regarding carbon capture and storage. The absorption can further expand by using crushed and recycled concrete as an aggregate in new concrete. Concrete is nearly 100 % recyclable. Nowadays recycled concrete is mainly used as aggregates in concrete and as fillers for various building purposes. Regarding to Norwegian concrete industry, there has been a conceptual study for capture technologies in Norcem Brevik (Gassnova, 2019). The main purpose in this technology is to transport carbon from the plant to the North Sea and store the carbon temporary below the seabed. As we can see it is a lot of innovation ongoing to transform the concrete industry to become more carbon neutral.

To avoid depleting non-renewable resources the concrete industry must seek alternatives. Natural fibres provide a sustainable alternative to steel and glass fibres and alternative aggregates can save natural deposits to further generations. Natural fibres are obtained in nature and are renewable, available and low cost. Through this assignment, it will be given an overview of the natural fibres and aggregates that could serve as sustainable alternatives.

Concrete is a durable building material and generally offers great compressive strength. To assess the real environmental impact of the constructions, one must also consider the estimated lifespan of the construction. In principle, alternatives can be used that gives great reductions in carbon footprint but reduces the duration of the construction. Shortened lifespan that leads to the need to make replacements often has negative environmental impact. If built with the right quality, long-life designs are built, and costly maintenance work is avoided. High durability is therefore a positive contribution to both society, economy and environment.

The durability in concrete is affected by the quality of the concrete mixture. Addition of materials can impair the quality of concrete. It is therefore also relevant to consider in what extend we can tolerate quality decrease when exchanging conventional materials and incorporate alternative sustainable materials in the mixture. Some substitutes and aggregate can even improve the quality. However, for some applications durability and compression strength is less important as for others. Therefore, we also must consider whether we can compromise these properties for some applications.

Another occurrence that impacts the durability is the crack formation that happens in concrete. The cracks provide access of gases and liquids to entering the concrete. If the crack gets large enough the reinforcement is no longer protected by the concrete`s highly alkali environment and both the concrete and the reinforcement will deteriorate in the long run. Therefore, it is essential to control the crack width as soon as possible. This could be done by self-healing technology which will be reviewed later on.

Clinker is the main ingredient in cement. It is found that the amount of clinker that is used is directly proportional to the $CO_2$ emissions generated in cement manufacturing. From 2014 – 2017 the clinker-to-cement ratio increased by 0.5% per year (IEA, 2018). The cement industry already offers commercial alternatives to minimize the use of clinker in cement by blended cements and clinker substitutes. Most commonly are industrial by-products such as blast furnace slag and fly ash. Further on natural pozzolanic materials has been used instead of clinker. It has also been revealed that by optimized mixing combination of calcinated clay and limestone it is possible to displace up to 50 % of the clinker with the mixture of calcinated clay and limestone. (IEA, 2018). Still, one is expected an increasing clinker demand in the future. Admixtures that reduce the need of water content makes the concrete stronger without adding extra cement. In this paper alternative supplementary cementitious materials and alternative binders will be reviewed and an evaluation if these materials can offer reduced need of clinker in the future without compromising other attributes is analysed.

The industry can mitigate the effects of climate change and simultaneous meet the increasing need of concrete in the future by offering low carbon concrete and sustainable use of raw materials.

Sustainability is generally defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. The concept is composed of three pillars: environment, economy, and society.

In 2015 The United Nations made an agreement for 17 sustainable development goals with the agenda to protect the planet and ensure prosperity for all. Several of the goals are related to the concrete industry, this report has its main focus at the following:

- **Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation**

  Part of the goal is to make industries more sustainable, by increasing resource-use efficiency and adopting environmentally friendly technologies and processes. The concrete industry can meet this goal by reducing the use of limited recourses, finding alternative materials and reducing emissions and energy use associated with production and transport.
- **Goal 12: Ensure sustainable consumption and production patterns**

  This goal promotes resource and energy efficiency, to achieve, among other things, reduced future environmental costs. It implies that developed countries take lead in sustainable management of natural recourses and reduce waste generation by prevention, reduction, recycling and reuse.
- **Goal 13: Take urgent action to combat climate change and its impacts**

  The whole concrete industry is responsible to do whatever possible to contribute to combat climate change.

These, and all the other goals are the blueprint to achieve a more sustainable future, and it is important we achieve them by 2030 (UnitedNations, 2015).

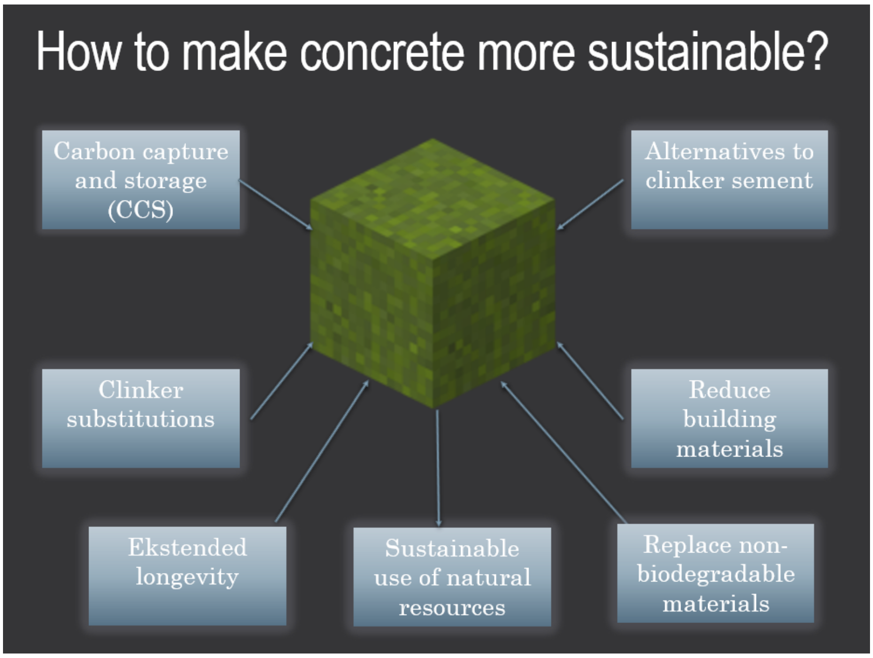


*Figure 2 Infographic how concrete can be made more sustainable*

There are many areas of concrete production in which we can make changes to reduce the $CO_2$ emissions. To develop concrete sustainability from a material perspective the main solutions we are focusing on in this paper is the following actions:

- Reducing the clinker amount needed by using substitutes in the cement
- Alternatives to regular clinker cement
- Improvement of durability to achieve an extended longevity in structures
- Finding bio-based alternatives to replace synthetic and non-biodegradable materials to increase recycling rate and reduce emissions and energy use related to production.

Other factors to have in mind while attempting to solve these problems are to seek alternatives to avoid depleting non-renewable resources, and possibly contribute to good waste management by reuse and recycling of materials.

Through a literature study we want to get an overall view of non-commercial methods that can support these solutions. We want to get a broad overview and a deeper understanding of different materials, how they are used today, current research and possible applications in the future. The key aspect of this is to assess how sustainability can be achieved in a context of bio-based materials that has been explored lately trough the answering question:

***How can we use bio-based materials to get more sustainable concrete?***

Important aspects of this question are how use of these materials reduce the environmental impact of the concrete, how they affect the mechanical abilities and durability of the concrete, and what possible applications there are for these types of concrete. Ethical and economic impacts will also be considered.

Attached is a draft for an article pulled from this paper. Before peer review the article will be further processed with help from our supervisor. This is our contribution to the field.

**Scope and limitations:**

- All main ingredients in concrete will be covered to some extent, including cement, aggregate, filler, binder, additives and admixtures as well as self-healing mechanisms and fibre reinforcement

- Only all-natural materials are used, excluding rubber, plastic etc. however, hybrid materials are included if the inclusion of such materials may give less negative environmental impact than the existing solutions. The main focus is on renewable bio-based materials, both by-products from other industries and materials from sustainable production methods. Even though the focus is on all-natural materials interconnecting non-natural materials can be featured to get a holistic view.
- The main focus is on relatively new solutions and current research, disregarding commonly used and already established methods and materials. Only including literature published after 2008, with the majority from after 2015, to get an up-to-date overview.
- The theme is extensive with many variables in terms of materials, techniques and applications. To get a good overview and to get a certain dive in the different topics rendered, the amount of materials and to what extent they are explored have been limited. Other materials may be mentioned but not research further. This is also due to time restrictions.
- It will not be excluded by country of origin, but only English and Norwegian literature have been included in regards of language
- Discarding research that clearly has lack of foundation such as Peer-review nor reliable references.
- Quantitative research is used when reviewing the materials properties

# 2 Theoretical basis

In this chapter we explain the theoretical basis necessary for understanding the following chapters.

## 2.1 Concrete Technology

Concrete is a composite material that is assembled by cement, water, sand, stone and small amounts of additions that are mixed. The constituents are often local and therefore offers a span of characteristics, the materials that is used and the mixing ratio is therefore essential to the concrete’s characteristics. Based on this, it is important to have knowledge of the material's micro and macro structure to understand the basic characteristics and how the concrete is affected when the constituent material structure and the mixing ratio changes. Pressure failure in concrete is caused by differences in stiffness (E-module) between cement paste and the aggregate. Local concentrations of stress and overload in the cement paste causes small cracks in the interface between the cement paste and the aggregate. The particles in the aggregate prevent further cracking by distribute the energy into making finer cracks. This provides a distribution of stress and prevents spontaneous failure (Maage and Norheim, 2015, Maage, 2015). Based on application, one must consider the size and the density of the particles in the aggregate.

### 2.1.1 Cement

#### Water/cement ratio and formation of C-S-H

The quality of the concrete is essentially determined by the mixing ratio between water and cement. This interrelation is shortened w/c-ratio and is one of the most essential terms considering concrete technology. The w/c-ratio settles the strength on the binder in the concrete. To ensure a certain quality and strength on the concrete, one must maintain the given w/c-ratio.

Cement paste with w/c-ratio higher than 0.4 contains more water than necessary, and pores will occur in the concrete. The pores are important in the fresh concrete, as they play an important role in the absorption and retention of moisture. During initial hardening, the water will be gradually released from pores for cement hydration.

Hydration is the process when water and cement react, and the mixture solidifies and achieves its strength. When the cement hydrates a needle-shaped reaction mass appears on the surface of the cement grain. This is called cement gel. Cement gel contains of both solid and loose crystals. The solid crystals are calcium silica hydrate formation that give the concrete strength, stiffness and durability. This formation is shortened C-S-H. The loose crystals make the concrete alkalic which is an advantage for reinforcement of steel by preventing corrosion. The effect of high and low w/c-ratio in cement paste is illustrated in *Figure 3*. Hardened concrete contains an amount of anhydrous cement due to the w/c-ratio.

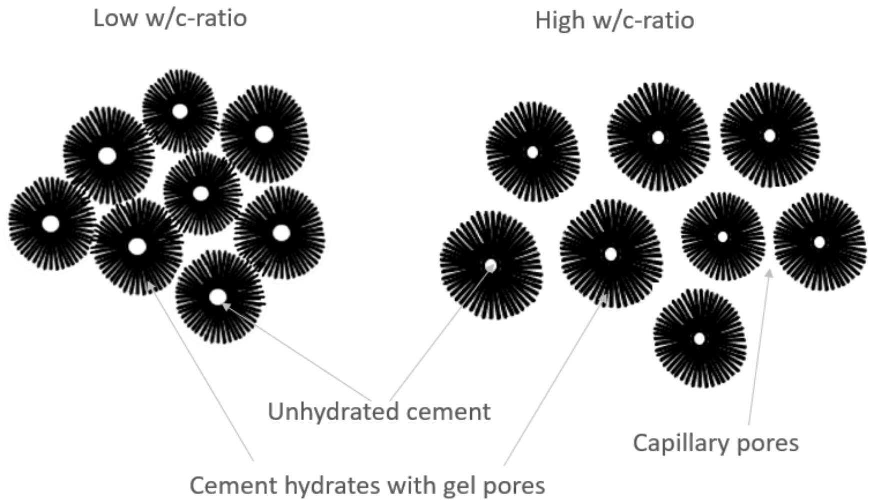


*Figure 3 Cement paste with high and low w/c-ratio*

To reduce water remained after hydration, it is important to reduce size and number of pores in the concrete, which will increase density and strength and results higher durability. This can be obtained by decreasing w/c-ratio or addition of certain ingredients which create more C-S-H.

### 2.1.2 Binder

Cement is a binder itself. Most common used cement is Ordinary Portland Cement (OPC) and is used as reference in many studies of cement replacement materials. Bio-based materials may show the same binding characteristics as cement in certain mixtures.

#### Mass ratio

Under proportioning of concrete with required properties, the process of selecting quantity of cement, water, sand and coarse aggregate to be carefully monitored. Mass ratio is important to control quantity of one solid compared with another solid in the mixture. It is defined by a constituent divided by the total mass of other constituents in a mixture.

Additions in the concrete is often stated as a ratio of relative content of the addition by the content of Cementous materials. In this thesis this ratio is referred by as m% with the given formula:

$$m\% = \frac{\text{content of the addtion}}{\text{content of cementous materials}} \text{x}100\%$$

In concrete industry it is interesting to study cement replacement for sustainability, and weight percentage are often used as measurement of how much mass of a certain material replaces cement. Example 10 % fly ash has replaced cement = fly ash 10 wt% (cement).

### 2.1.3 Admixtures

Admixtures are materials in the form of powder or fluids that are added to the concrete to give it certain characteristics not obtainable with plain concrete mixes. Admixtures are defined as additions made as the concrete mix is being prepared, either before or during mixing. The main reason for use of admixtures are to modify the properties of the concrete, such as durability, workability or strength characteristics. Some effects achieved by the admixtures, may be achieved by change of the w/c-ratio, using different aggregates or type of cement, but it will be more cost effective to use an admixture in the mortar. Natural admixtures are normally abbreviated as NAD.

Admixtures are classified as water-reducers, accelerators, retarders, plasticizers, air-entraining agents and a large group of specialty category.

### 2.1.4 Additives

The main difference between admixtures and additives is the time of addition. Admixtures are added to concrete mixture while mixing, when additives are added to cement during manufacturing to get new properties for the cement. A wide variety of additives can be incorporated, such as accelerators, retarders, dispersants, extenders, weighting agents, gels, foamers, and fluid loss additives.

### 2.1.5 Fillers

Fillers are mainly used to replace the cement, to lower the $CO_2$ footprint of the concrete. The fillers can impact or react with cement, reduce amount of cement without reducing strength and improve the properties in fresh concrete by for example improve particle packing. Commonly used fillers today are different stone dust or limestone powder (LP), pozzolanic fillers, such as micro silica/silica fume (SF), fly ash (FA), metakaolin (MK) and blast-furnace slag (GGBS). Worldwide the FA is most commonly used, due to high availability from the coal power plants, but since Norway has a large ferro-silicon industry, silica fume is mainly used in domestically produced concrete in Norway.

### 2.1.6 Aggregates

Aggregate is a structural filler that takes up about 65-75 % of the total volume of concrete. Size and shape of the aggregate and how cement paste bind aggregate together, have significant impact on the workability, strength, weight, shrinkage and durability of the concrete.

Stones and crushed rock are appropriate for use in concrete, but lightweight aggregates can also be successfully used. Soft, brittle or reactive materials may create challenges in the concrete. Crushed stone production is responsible for fine fugitive dust emissions that lead to health hazards for the workers and surrounding population and affect the climate. These emissions are connected to both the mining activity, the transportation and the crushing of the stone. Emissions because of aggregate production can be reduced by replacing these aggregates with other, more sustainable alternatives (Dhir et al., 2020).

## 2.2 Reinforcement

Concrete alone can absorb great compression forces but is weak in tension by only 10% of its compression force. For this reason, reinforcement is added to resist tensile stresses caused by bending forces which result in cracking and failure.

Steel rods, bars or mesh are often used as reinforcement for load-bearing structures, because of their high strength. For other structures, such as on ground floors and pavement, fibre reinforcement is commonly used. Fibre reinforced concrete ensures a concrete with far greater resistance to cracking than standard reinforced concrete.

When a load is acted repeatedly on a reinforced concrete structure, the tensile reinforcement in it is also stressed and released repeatedly. This causes microcracks that can further develop into larger cracks. Hence, reinforcement should improve both compressive, flexural and tensile strength, depending on the application of the concrete.

## 2.3 Modification and analysis methods

**Alkali treatment**: Materials are immersed in $Ca\ (OH)_2$ or NaOH solution at controlled temperature and then rinsed and air dried. This removes impurities and amorphous constituents from the fibres and increases crystallinity (Ferreira et al., 2015, Yan et al., 2016).

**Carbonization**: A pyrolysis technology where the organic material goes through thermal decomposition. Material are heated in non-oxygen conditions, and all non-carbon parts will be burned, and the rest product is pure carbon. The process eliminates conditions for microbial populations and fungal growth. It is considered as a cheap and reliable method. In all bio-based materials it resulting a decrease in water absorption, and leads to higher rot resistance (Fan Wu, 2018)

**$CO_2$ curing**: Done by having concrete block in a certain air pressure for a certain time. Example 100 % $CO_2$ at 1.3 bar for 24 hr. By use of silica gel, it will be possible to contain constant moisture (Wang et al., 2020).

**Hornification**: Materials are placed in water until they reach maximum absorption capacity, then dried at high temperatures. This process is repeated several times. Hornification is effective to modify the fibre microstructure, giving dimensional stability and increasing the elastic and frictional bond between fibre and matrix (Ferreira et al., 2015).

**Lyophilization**: A freeze-drying process of a medium. It consists of two main phases, freezing and drying. First phase all water is turned into ice, and the medium will crystalize. In drying phase the water evaporates (Neeraja, 2016).

**Polymer impregnation**: Materials are immersed in aqueous polymer and dried. There are different polymers used for this treatment method (Ferreira et al., 2015).

**Saltwater treatment:** Material is submerged in saltwater for several hours at controlled temperatures.

**Silica coating**: By 2.6 % aqueous tetraethyl orthosilicate emulsions in several baths of different pH, during a certain time of hours (Boix et al., 2020).

**Rapid Chloride permeability test (RCPT)**: Monitor the electrical current that pass through a specific piece of concrete sample. This will indicate the chloride permeability.

**Thermogravimetric analysis (TGA)**: Measures change in a mass based at changes in temperature. Normally controlled by weight loss under high temperatures. Method are used to identify adsorption, dehydration, evaporation, sublimation and chemical reactions (Raade, 2019).

## 2.4 Self-healing concrete

Concrete is exposed to cracking because of the issues considering the brittle behaviour and low tensile strength in concrete. Iron reinforcement is exposed to corrosion when left unprotected by the concrete shielding properties when cracks make access to the inner concrete. Solutions that can limit and heal the cracks provide high durability and is a valued solution seen from a sustainability perspective. There are generally two solutions of self-healing that can occur in cementitious materials, autogenous and autonomous. The cracks can seal due to swelling of the cement matrix, secondary hydration and precipitation of calcium carbonate - limestone.

### 2.4.1 **Autogenous healing**

The autogenous self-healing process is a natural process of crack repair in concrete and involve the original components of the materials and concerns all methods that use the self-healing capability of the matrix itself. The self-healing can happen in the presence of water. There are several studies on the topic of autogenous healing. Some of the repair is achieved by swelling of the cement near the cracks and/or that the cracks are filled with fine particles of broken concrete produced in the cracking process or transported to the crack by water. The main cause is the delayed hydration in cement that can occur by two mechanisms as visualized in *figure 4*. The first mechanism is when the anhydrous cement is exposed to water and the following formation of calcium silicate hydrate (C-S-H). The second mechanism is the precipitation of calcium carbonate ($CaCO_3$), due to the reaction of calcium ions/calcium hydroxide with carbon dioxide ($CO_2$), that either is present in the atmosphere or dissolved in water ($H_2O$). The first mechanism will often happen in cracks in early age concrete, the second will occur in old-cracked concrete (Ferrara, 2018).

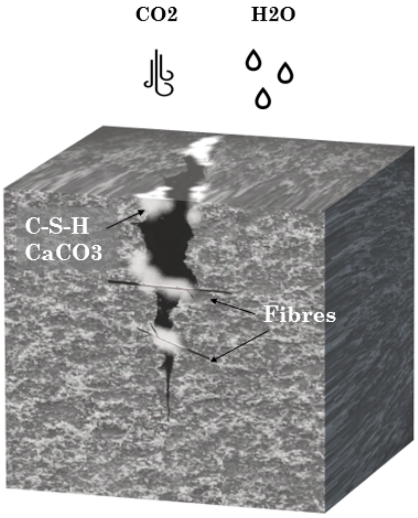


*Figure 4 Self-healing mechanism in concrete*

### 2.4.2 Autonomous healing

The autonomous self-healing process is when the self-healing crack repair is based on additives. Different healing agents can be used with different efficiency. The self-healing techniques can be based on either a biological process or a chemical process.

Several healing agents have been investigated with different techniques. The healing agent is incorporated directly in the concrete or by using a carrier compound. A carrier compound is used to protect healing agents from the mechanical forces by mixing and hydration process. Two different techniques can be used, capsulation or absorption. When the adsorption method is used, the carrier media is saturated with the healing agent suspension. Encapsulation is a technology using capsules containing a healing agent to produce a self-healing concrete system.

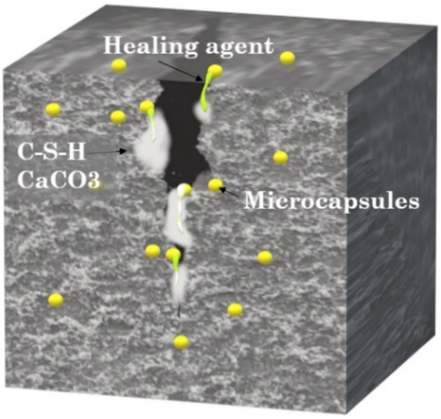


*Figure 5 Self-healing with microcapsules*

The principle for self-healing with capsules is that when the cracks starts developing in the concrete the capsules in the concrete crushes and the healing agent is released in the cracks and start to seal the cracks as illustrated in *figure 5.*

To ensure the healing-agent to be discharged at the right time the shell material must be hard enough to resist the pressure in the mixing and hydration process and weak enough to rupture when the crack occurs.

# 3 Review of bio-based materials for sustainable concrete

## 3.1 Method

This thesis is a pure literature review. To get a relevant selection of which bio-based materials and methods that have been tested and used worldwide we started with a wide selection of literature and narrowed the selection down using qualitative methodology when analysing the articles, research materials and other sources we gathered. An advantage of this methodology is that it provides flexibility in data collection. When the analysis reveals something that we want to go deeper into, we can search even more specifically. In the process of narrowing the selection of sources we must ensure representativeness and that the information has high qualitative information. In this process we also use quantitative methodology by categorise and count similar use of materials/methods. In this way we can provide a summary of the data we want to present.

The literature study as a method is appropriate to identify the state-of-the-art knowledge on the topic like we intend to. This is done through presenting empirical findings to the research question and determinate in what extend there are some trends considering the topic. The outcome can lead to the need of more research or innovation. In this thesis possible through suggesting alternative use of materials or combinations of materials.

Databases used are Ei Compendex and Google Scholar, because these databases provide a diverse and up-to-date selection of relevant literature. The reference section for each article was used to find additional articles within same topic. Technology journals were studied and the most relevant were included in the reference list.

We started with a broad search on the main ingredients of concrete (admixtures, fibres, and so on), combined with “sustainable”. This gave an overview of what exists on the subject. We then narrowed the search on all the different materials, combined with search words regarding the properties of the concrete, the different applications and the environmental impact.

The search process uncovered 1116 articles published from 1994 to 2020. After reading the abstracts, we narrowed down to the most relevant ones by limiting to the references within the scope of our thesis. Of references used 90% are published after 2015, and 60 % after 2018.

In a literature study the investigation is dependent on articles conducted by others and by selection and further use we must critically evaluate the sources. The foundation of our research is based our sources from the Ei Compendex database. This database provides access to peer reviewed and indexed publication, this is a method of quality assurance to validate academic work. Further on we assessed the authors, publisher or companies in the context of trustworthy and reliability.

Our research is based on a broad literature catch and several sources has been used for each topic to discover trends and similar results to answer the research question.

Following chapters present the findings.

## 3.2 Natural fibre reinforcement

Fibre reinforced concrete (FRC) is widely used. Natural fibres are obtained in nature and are renewable, available and low cost, and use of them as reinforcement in structural components have gone up the past decade. However, there are several shortcomings, such as high moisture content, inconsistent properties, uneven dispersion and in some cases poor bonding properties. It is difficult to produce good mathematical and numerical models to predict the mechanical properties, because of inaccurate data. Modelling the fibres accurately is impossible due to their differences (Lau et al., 2018).

Failure in strength properties in macro scale natural fibres can be traced to the development of damage zones or bonding zones. These zones have a size and the particle of fillers has an influence. If the fibres are too large, they do not exhibit surface reactivity. Therefor it is possible that nanocomposites with smaller sizes can offer better strength abilities. Nano scale fibres tend to meet some of the challenges seen with larger sized fibres such as low elastic modulus and poor compatibility between fibre and matrix (Hisseine et al., 2019).

Another challenge is the durability of the fibres, which have been attempted to improve through different kinds of treatment. Findings are that the treatment methods are expensive and hazardous, hence long-term durability has not yet been determined (Mohajerani et al., 2019).

The following chapters compile recent research on some of the most important natural fibres used and researched today. It is important to note that the different experiments used different grades of concrete, aggregates, admixtures and lengths and diameter of fibre etc., which sometimes make for contradicting results. Figures show compiled results from different tests and experiments.

### 3.2.1 Bamboo

Among the natural fibres, bamboo has the lowest density. It is flexible and lightweight, easy grown and harvested. It is also one of the fastest growing plants known, making it one of the most cost-effective construction materials available.

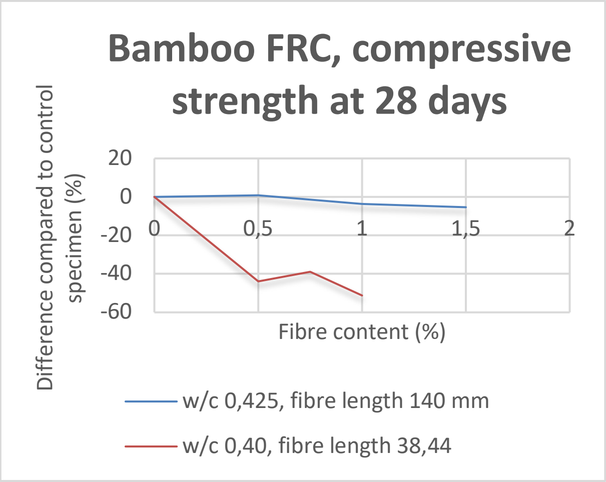


*Figure 6 Bamboo FRC, compressive strength, w/c 0.425 (Goh and Zulkornain, 2019), w/c 0.40 (Awoyera and Babalola, 2015)*

Incorporating bamboo fibres in the concrete reduces workability of the fresh mix, because the increase in fibre content enhances the cohesiveness and internal resistance. Compressive strength test yield varying results, but both flexural and tensile strength is improved. Compared to steel fibres the bamboo had significantly better results for both tensile and flexural strength (Ede et al., 2019, Goh and Zulkornain, 2019, Awoyera and Babalola, 2015).

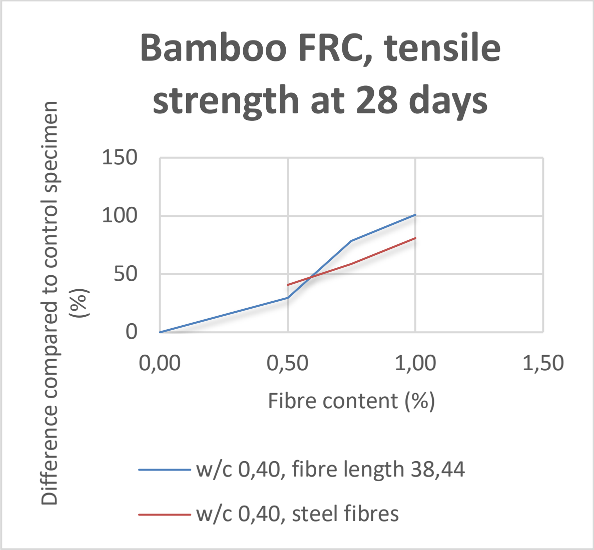


*Figure 7 Bamboo FRC, tensile strength compared to steel fibres (Awoyera and Babalola, 2015)*

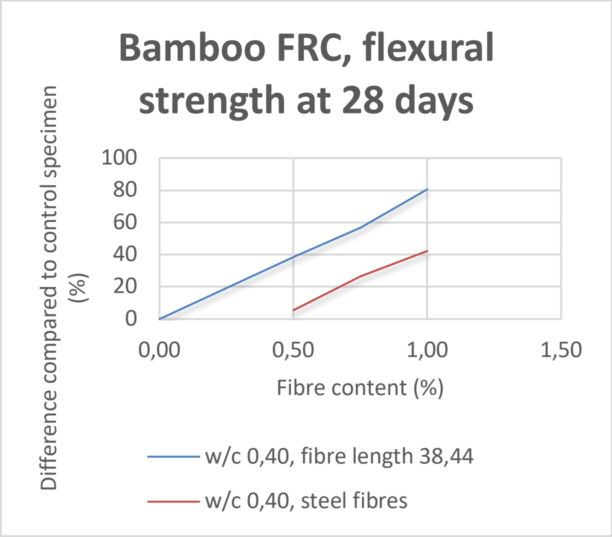


*Figure 8 Bamboo FRC, flexural strength Compared to steel fibres (Awoyera and Babalola, 2015)*

Before utilizing the bamboo in concrete, the fibres need to be treated to prevent long term deterioration and make them more durable. This prevents the fibres from absorbing water meant for the hydration process in the concrete (Goh and Zulkornain, 2019, Ede et al., 2019).

### 3.2.2 Sisal

Fibres are extracted from leaves of sisal plants, which grow in hot and dry areas.

Slump value and water absorption tests show a decrease in workability with an increase of fibres in the mix. A 2 % addition of sisal fibres resulted in a 78.3 % reduction in slump value and a 49.2 % increase in water absorption. Decreased density with increase of sisal fibres makes the concrete lighter (Okeola et al., 2018).

Different compressive strength test gives varying results, while tensile strength is clearly increased with addition of fibres. Average flexural load is significantly increased with the addition of fibres and modulus of elasticity is increased (Okeola et al., 2018, Sabarish et al., 2019).

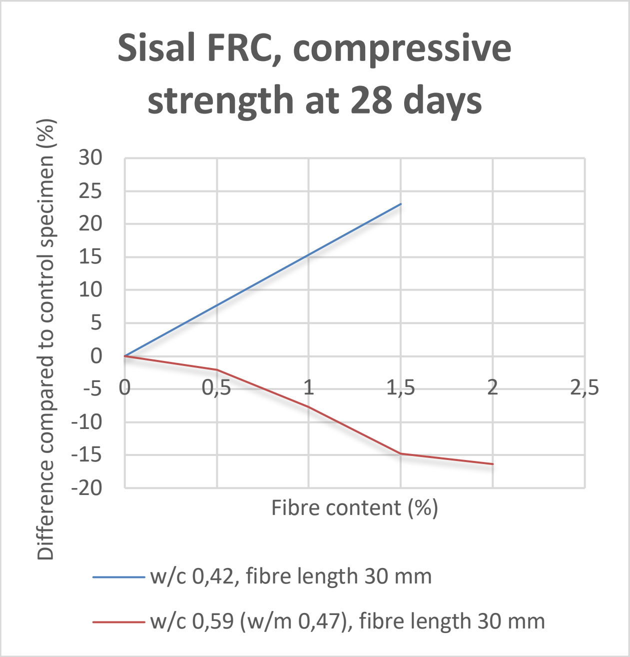


*Figure 9 Sisal FRC, compressive strength, w/c 0.42 (Sabarish et al., 2019), w/c 0.59 (Okeola et al., 2018)*

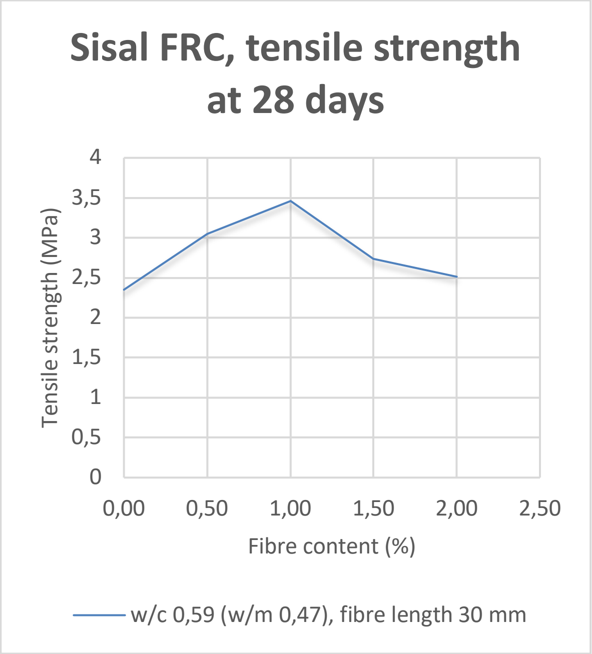


*Figure 10 Sisal FRC, tensile strength, (Okeola et al., 2018)*

Different treatments of the fibres have been tested to improve durability, and conclude with the fact that durability remains poor (de Klerk et al., 2020).

### 3.2.3 Coconut (coir)

Coconut fibre (CF) is attained from the coconut husk and is among the natural fibres with the highest toughness. This plant fibre is available in large quantities, especially in Asia, Africa and South America. Coir fibres can be used both treated and untreated. The treated fibres are immersed in NaOH, dried and rinsed several times before use.

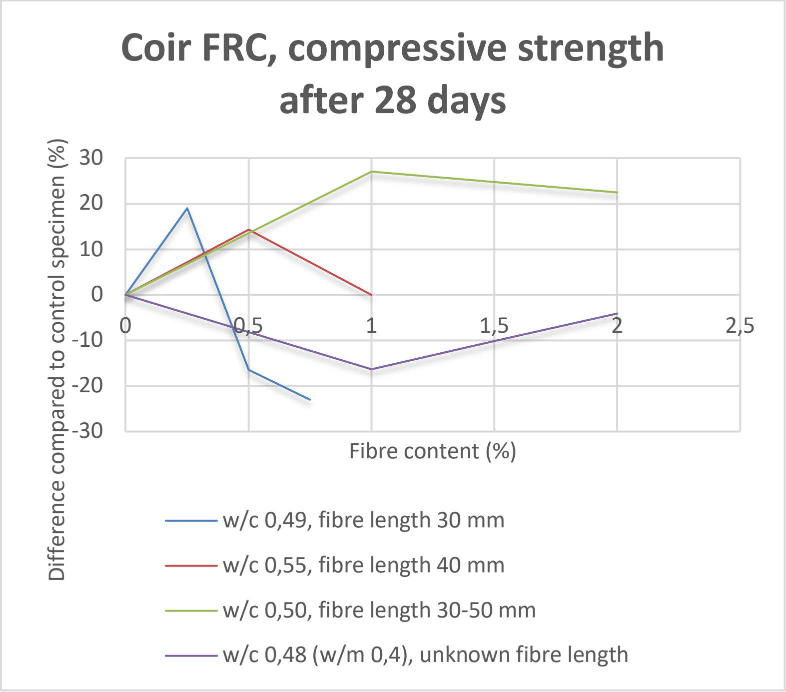


*Figure 11 Coconut FRC, compressive strength, w/c 0.49 (Rumbayan et al., 2019), w/c 0.55(BABAFEMI et al., 2019) , w/c 0.50 (Mahalakshmi and Devi, 2019) , w/c 0.48 (Sai et al., 2018)*

Slump tests show that addition of CF reduces the workability of the fresh mix. However, in mix with alkali-treated fibres the slump values only decrease after adding 0.5 % coir fibre. According to some of the research the mix can be made more workable by increasing w/c-ratio. Coir is a lightweight material, and the weight of the concrete decreases with the increase of coir replacement (Rumbayan et al., 2019, BABAFEMI et al., 2019).

In strength tests there is a pattern to most of the results; the compressive strength increases until we reach the optimal addition of fibres, then decreases. In experiments comparing treated and untreated fibres, the untreated coir concrete had a much higher increase than the treated coir. Flexural and tensile strength tests show the same pattern as the compressive tests (BABAFEMI et al., 2019, Rumbayan et al., 2019, Mahalakshmi and Devi, 2019, Hardjasaputra et al., 2017).

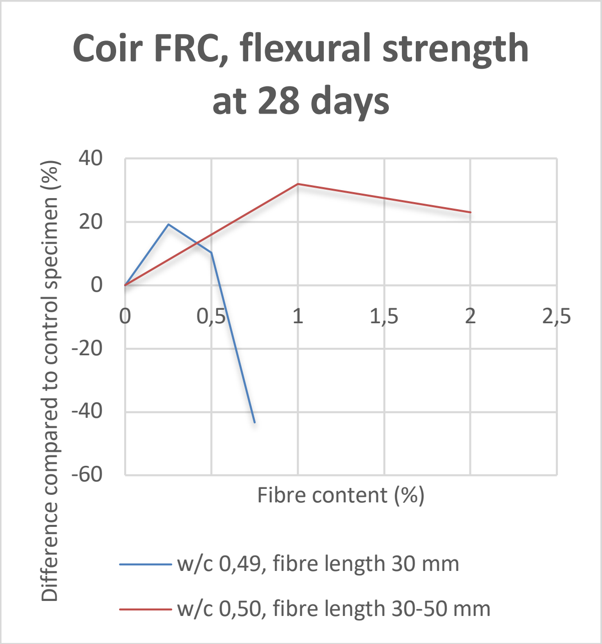


*Figure 12 Coconut FRC, flexural strength, w/c 0.49 (Rumbayan et al., 2019),w/c 0.50 (Mahalakshmi and Devi, 2019)*

Tests performed by immersion in MgSO4 and HCL (separate tests) after curing in water show that in terms of mass loss and compressive strength loss the CF improved the concretes resistance to sulphate and acid attack at all concentrations (BABAFEMI et al., 2019, Mahalakshmi and Devi, 2019).

Coir fibres have proved to have good insulation properties and maintain their tensile capacity while wet. Since the fibres have a high content of lignin, they have a slower degradation process than many other fibres (Mohajerani et al., 2019).

### 3.2.4 **Jute**

Jute fibres are long vegetable fibres extracted from the exterior of the jute plant and can be spun into strong threads. Used in construction they can contribute to a porous material suitable for filtration and drainage (Mohajerani et al., 2019).

Strength tests show that jute fibres can better the mechanical properties of concrete, however more than 0.25 % addition or fibres longer than 15 mm will reduce the properties (Zakaria et al., 2018).

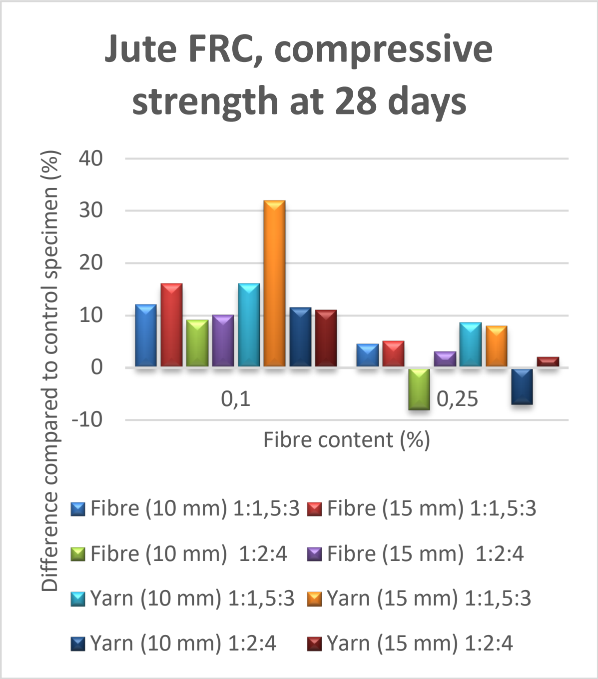


*Figure 13 Jute FRC, compressive strength (Zakaria et al., 2018)*

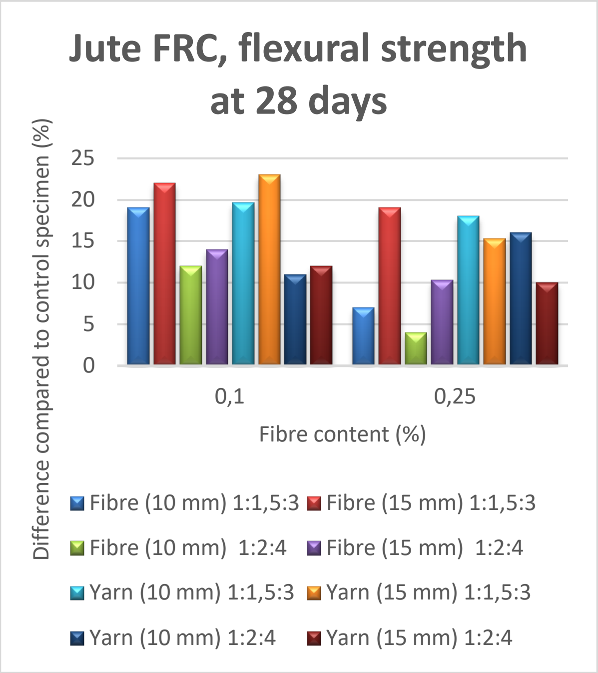


*Figure 14 Jute FRC, flexural strength (Zakaria et al., 2018)*

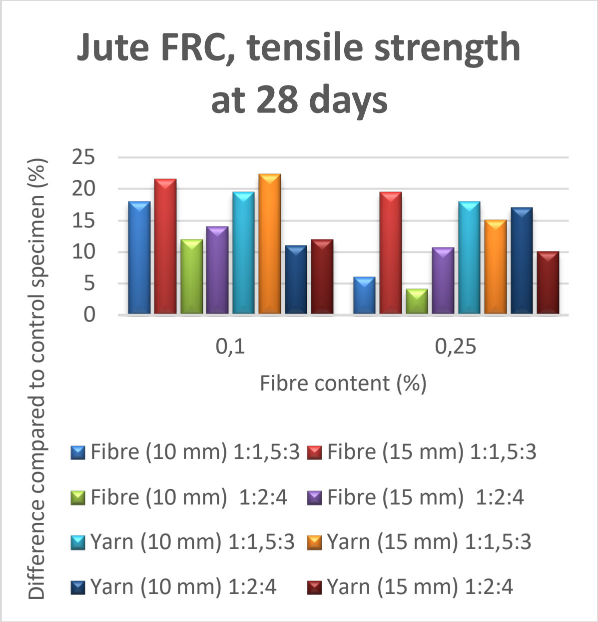


*Figure 15 Jute FRC, tensile strength (Zakaria et al., 2018)*

Jute fibres have been tested on different applications, and it is shown that jute fibre reinforced polymers (JFRP) is very effective to enhance ultimate load capacity in RC beams, and that confining concrete cylinders in JFRP can increase the compressive strength by 42 % (Joykląd et al., 2019).

It has also been concluded with the fact that it is possible to control the physical properties of the jute fibre through choice of treatment (El Messiry and Fadel, 2019).

### 3.2.5 Flax

Flax is soft, flexible and grown in colder environments.

A study researching the degradation of flax fibres and fabric under different exposures revealed that immersion in saltwater and alkali water does not lead to a significant decay of tensile strength. Immersion in hydraulic-lime or cement mortar lead to a reduction over 7 days but remained steady until 56 days. Immersion at a temperature of 55°C lead to significant degradation. The conclusion is that flax can be utilised in TRM (textile reinforced mortar) systems. Another study reveals that flax textile grids is a promising reinforcement in TRM systems, and that increased volume of reinforcement does not lead to reduction in strength. The fibres have good durability, the bond between the fibres and the paste was efficient and there was no evidence of deep mineralization of the fibres over the first year (Ferrara et al., 2019b, Ferrara et al., 2019a, Sabathier et al., 2017).

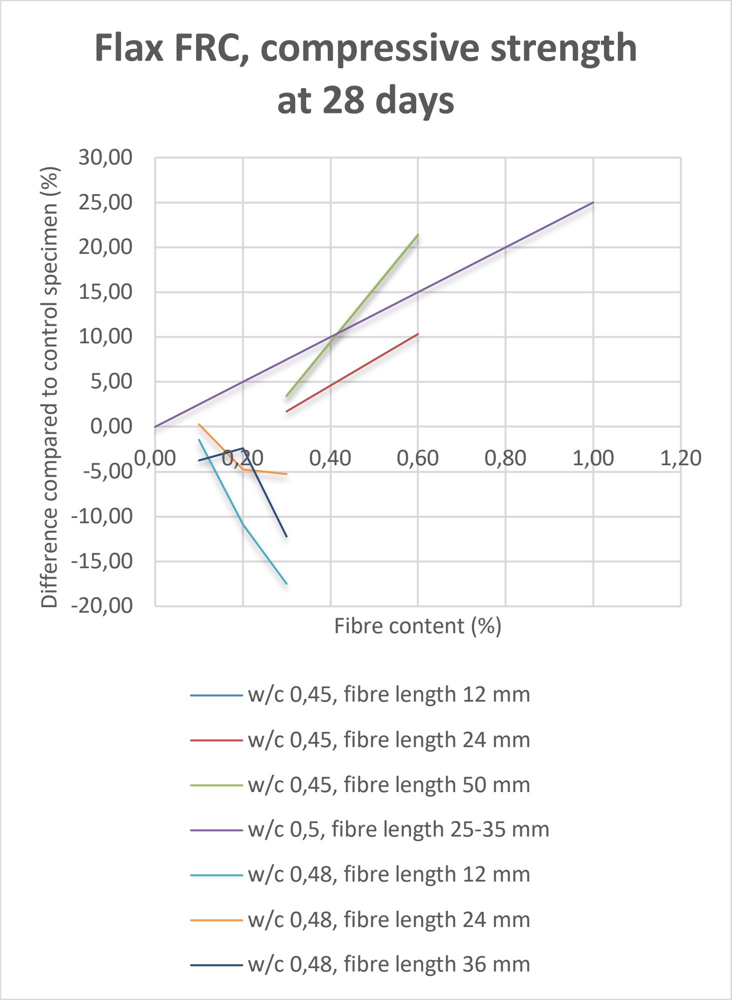


*Figure 16 Flax FRC, compressive strength, w/c 0.45 (Kouta et al., 2019), w/c 0.5 (Sabathier et al., 2017), w/c 0.48 (Page et al., 2017)*

Fibres can absorb water 130 % of their dry mass, however absorption after 24hrs is considered to be sufficiently stable. The water absorption of the fibres clearly affects workability. This can be avoided by changing the mix design. Fibres also led to increased porosity in the concrete (Page et al., 2017).

Results from different studies show that compressive strength can both increase and decline, depending on mix design. The overall trend is that the flexural strength increases (Kouta et al., 2019, Sabathier et al., 2017, Page et al., 2017).

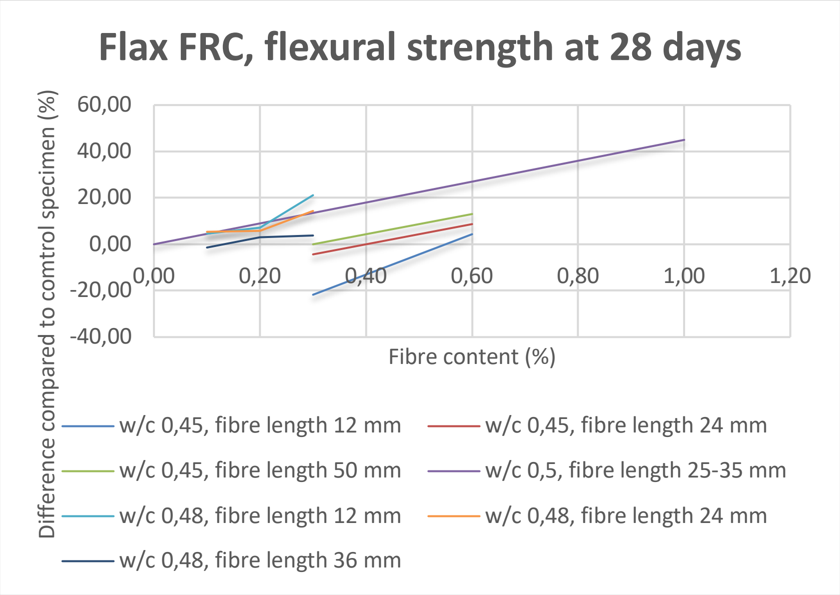


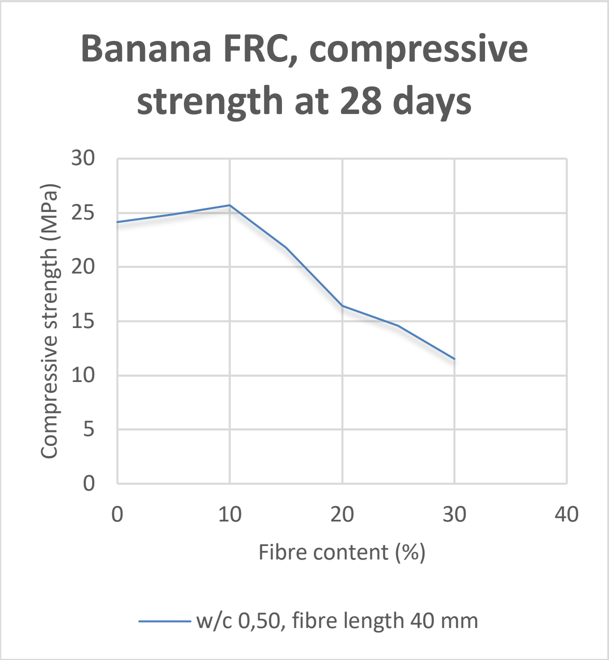
*Figure 17 Flax FRC, flexural strength, w/c 0.45 (Kouta et al., 2019), w/c 0.5 (Sabathier et al., 2017), w/c 0.48 (Page et al., 2017)*

### 3.2.6 Banana

Banana fibres are incredibly durable and one of the world's strongest natural fibres.

Tests performed on concrete show that incorporating 0.5 % Banana fibre led to reduced acid resistance, reduced compressive strength after exposure to both magnesium sulphate, sodium chloride and sulphuric acid and reduced compressive strength after exposing to high temperatures (Anowai et al., 2017).

Test results show the same pattern for compressive and tensile strength. Adding banana fibres up to a certain point can increase strength (Chacko et al., 2016).



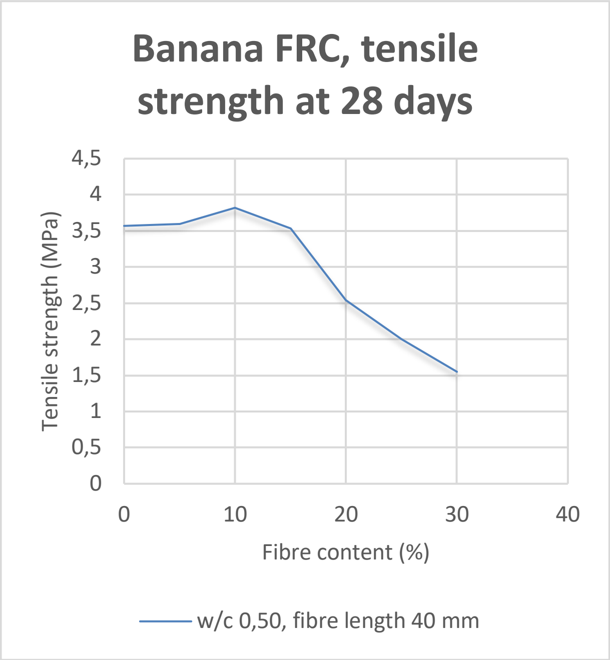


*Figure 18 Banana FRC, compressive strength (Chacko et al., 2016)*

*Figure 19 Banana FRC, tensile strength (Chacko et al., 2016)*

### 3.2.7 Kenaf

Kenaf is a cellulose fibre mostly grown in tropical environments. It is commercially available, economically efficient, quickly grown and easily harvested. A project initiated by Harusmas Agro Sdn. Bhd. (HASB), who imported different varieties of Kenaf from around the world, shows that the crops have good adaptability to local conditions (JECComposites, 2011).

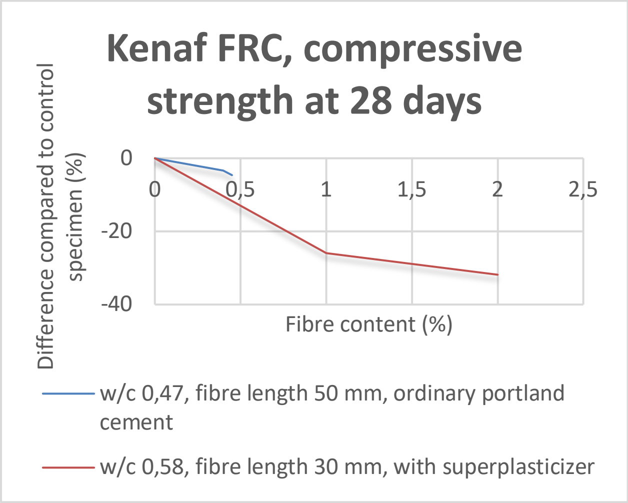


*Figure 20 Kenaf FRC, compressive strength, w/c 0.47 (Mahzabin et al., 2019), w/c 0.58 (Syed Mohsin et al., 2018)*

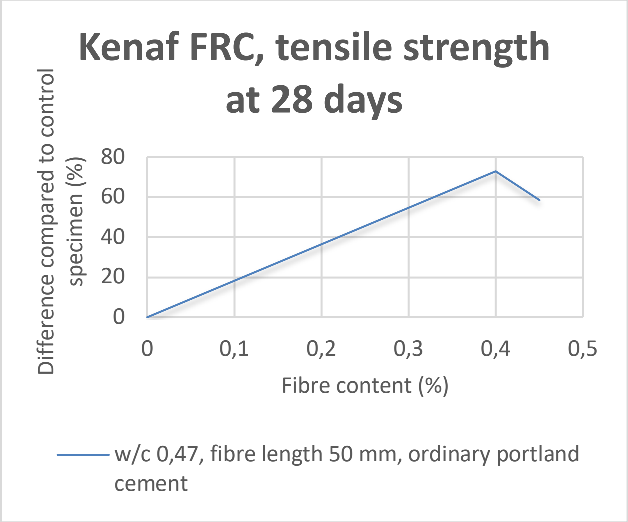


*Figure 21 Kenaf FRC, Tensile strength (Mahzabin et al., 2019)*

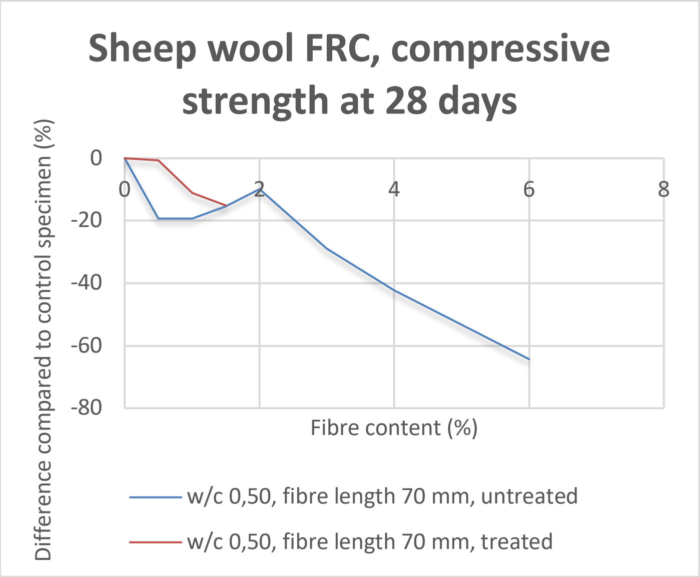
Incorporating kenaf fibres generally leads to increased water absorption and decreased workability. To maintain w/c-ratio and achieve required slump values, a superplasticizer can be added to the mix. The fibres are treated in NaOH to remove impurities and modify the surface of the fibres.

The concretes mechanical abilities are affected, resulting in decreased compressive strength, but increased flexural and tensile strength and ultimate load capacity. Although the compressive strength is decreased, some researchers have managed to obtain targeted compressive strength. For concrete slabs the fibres also reduce cracking propagation and improves ductility and significantly increased first and ultimate crack resistance (Syed Mohsin et al., 2018, Mahzabin et al., 2019, Muda et al., 2016).

Research on the effect of different curing conditions show that curing conditions play a big part in the outcome, especially when it comes to mechanical properties (Ahmad et al., 2019).

### 3.2.8 Sheep wool

Studies on sheep wool fibres show that they generally improve the mechanical properties of the concrete, with the exception of decreased workability and declining compressive strength. The flexural and tensile strength is moderately to remarkably enhanced compared to control specimens, depending on mix design and percent inclusion.



Modified with saltwater treatment the fibres have improved properties, and the compressive strength loss is reduced. The fibres also gave better ductility and higher energy absorption. The adhesion between the sheep wool fibres and the cement paste was satisfactory for structural application (Alyousef et al., 2020, Alyousef et al., 2019).

*Figure 22 Sheep wool FRC, compressive strength (Alyousef et al., 2020)*

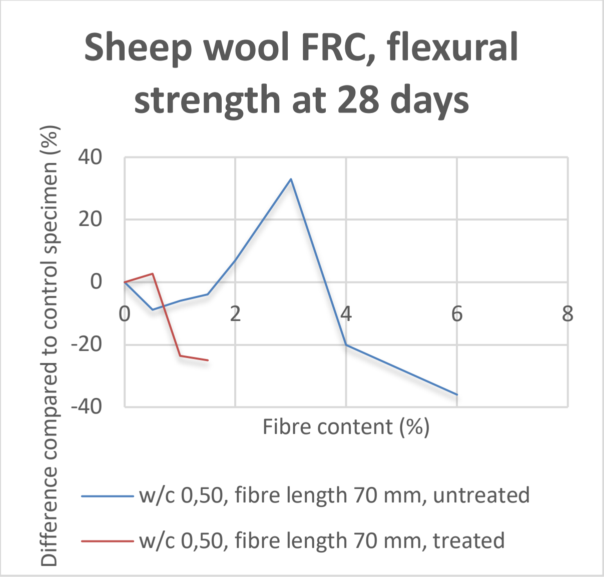


*Figure 23 Sheep wool FRC, flexural strength (Alyousef et al., 2020)*

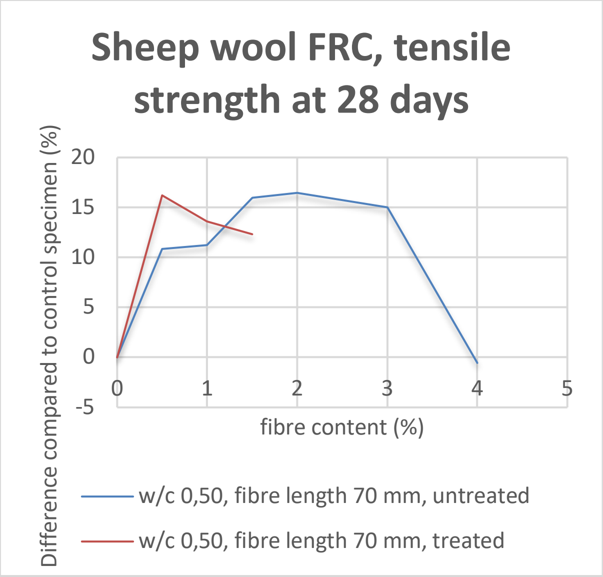


*Figure 24 Sheep wool FRC, tensile strength (Alyousef et al., 2020)*

### 3.2.9 Other fibres

There are many other fibres available that also have a potential for use in fibre reinforced concrete, among them palm, sugarcane bagasse, alfa and wheat straw.

Oil palm or date palm fibres show potential with improved strength, ductility and energy absorption. However, the palm fibres lead to reduced workability and the mechanical abilities are severely affected by the alkaline environment in the cement (Aljalawi, 2019, Kriker et al., 2008, Momoh and Osofero, 2019).

Sugarcane bagasse shows similar abilities as many of the other fibres, with decreased compressive strength and increased tensile strength (Sheikh Khalid et al., 2017).

Alfa follows the same pattern as many other fibres; decreased workability and compressive strength, increased tensile strength and porosity. It leads to delayed early shrinkage and cracking, but also a loss of durability with time (Khelifa et al., 2018).

Wheat straw gives increased water absorption, improved strength, increased fire resistance and is energy effective, but needs to be treated to avoid decay (Chin and Nepal, 2019, Mohajerani et al., 2019).

Basalt fibre is different from the other natural fibres as it is a volcanic and igneous mineral naturally found and available on a global scale. Reinforcing concrete with basalt fibres inhibits generation and propagation of cracks and gives better durability as well as superior resistance to blast loading, impact loading and high temperatures. Wrapping concrete cylinders in basalt fibres give increased compressive strength, improved load-deflection behaviour, enhanced stiffness and increased ductility. Studies show that two layers of basalt fibre give better performance than one layer of carbon fibre fabric (Krishnan et al., 2019, Hao et al., 2019, Mohajerani et al., 2019, John and Dharmar, 2020).

### 3.2.10 **Summary**

Following figures summarize the maximum improvement compared to the control specimen of each experiment.

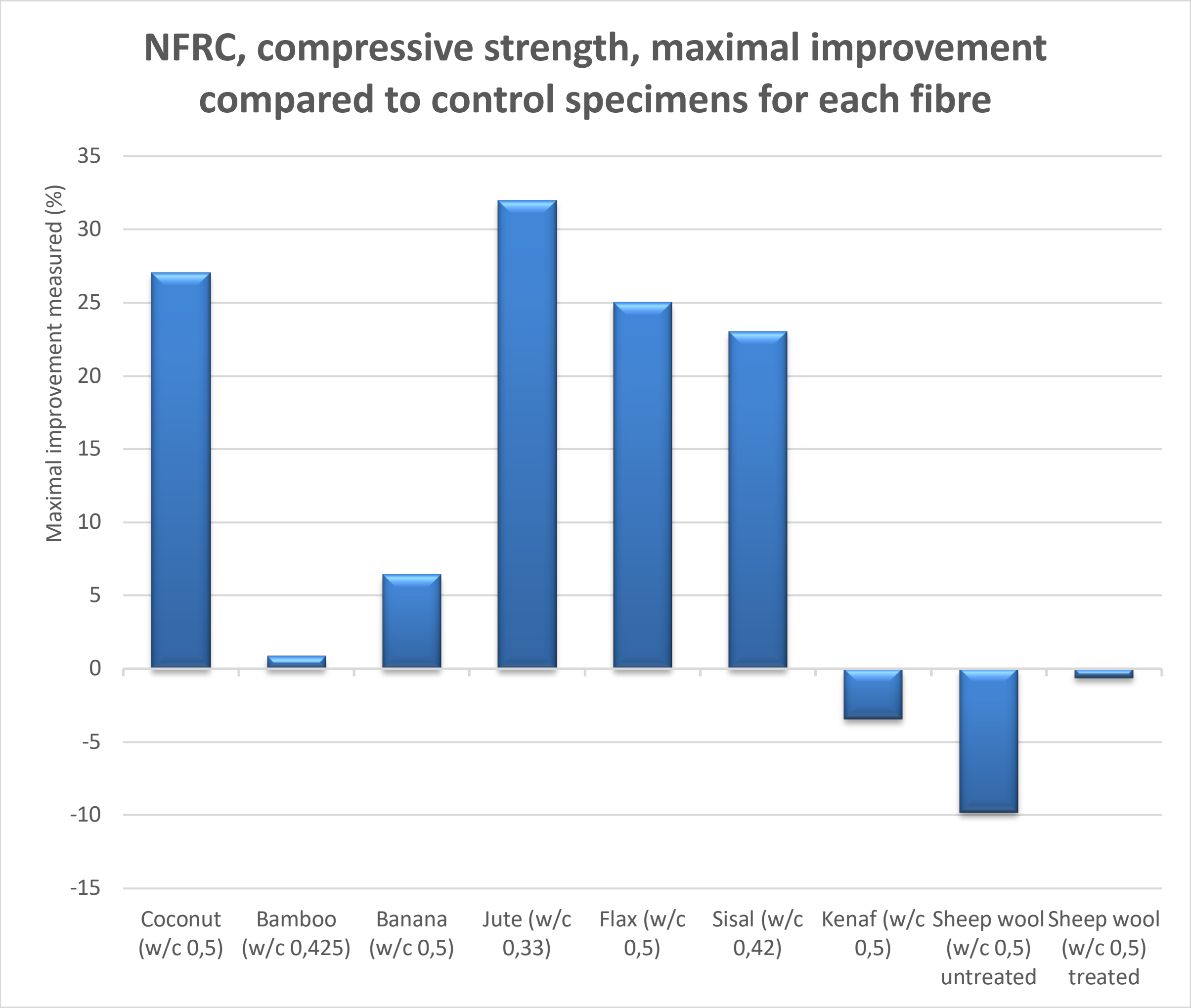


*Figure 25 Compressive strength, natural fibre reinforced concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Goh and Zulkornain, 2019), Banana (Chacko et al., 2016), Jute (Zakaria et al., 2018), Flax (Sabathier et al., 2017), Sisal (Sabarish et al., 2019), Kenaf (Mahzabin et al., 2019), Sheep wool (Alyousef et al., 2020)*

Maximal improvement for compressive strength: No plasticisers or viscosity modifying agents were used in these mixes. Similar curing conditions in research where this information was given. Cured in water tank or water impermeable plastic bags.

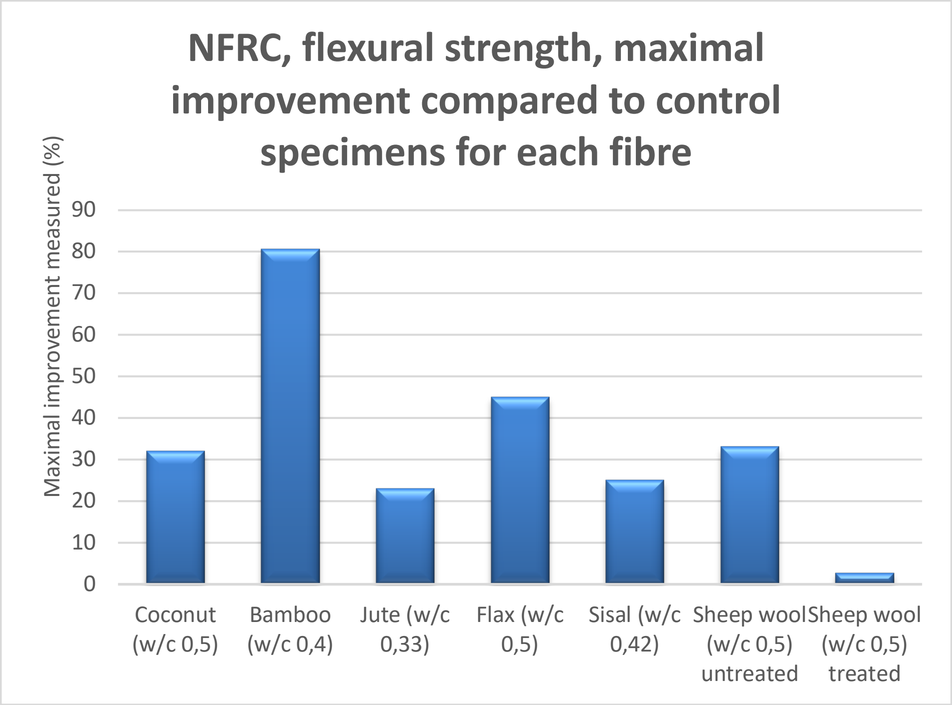


*Figure 26 Flexural strength, natural fibre reinforced concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Awoyera and Babalola, 2015), Jute (Zakaria et al., 2018), Flax (Sabathier et al., 2017), Sisal (Sabarish et al., 2019), Sheep wool (Alyousef et al., 2020)*

Maximal improvement for flexural strength: No plasticisers or viscosity modifying agents were used in these mixes. Similar curing conditions where this information was given. Cured in water tank or water impermeable plastic bags.

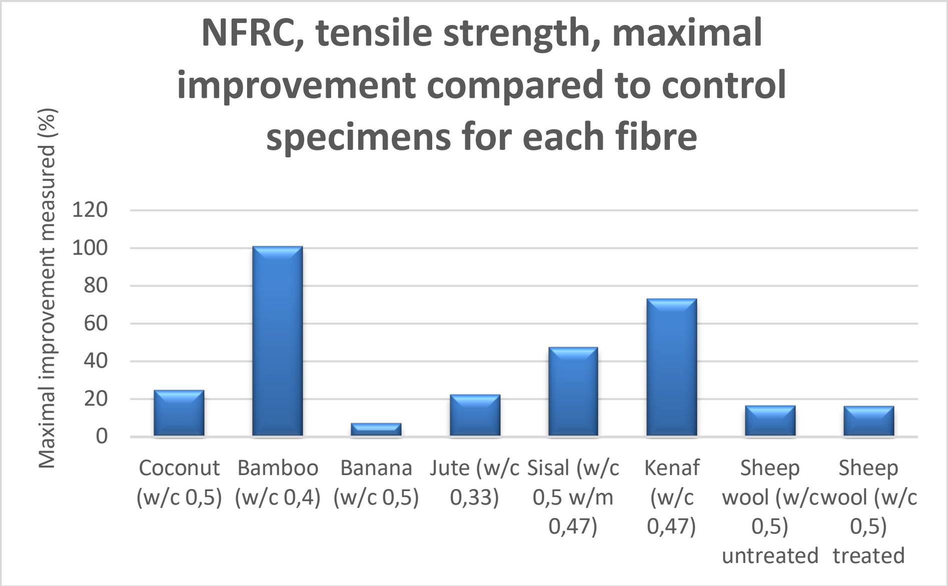


*Figure 27 Tensile strength, natural fibre reinforced concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Awoyera and Babalola, 2015), Banana (Chacko et al., 2016), Jute (Zakaria et al., 2018), Sisal (Okeola et al., 2018), Kenaf (Mahzabin et al., 2019), Sheep wool (Alyousef et al., 2020)*

Maximal improvement for tensile strength: The bamboo and sisal concrete contained a superplasticizer, and the sisal concrete also contained silica fume. Similar curing conditions were used; cured in water tank.

### 3.2.11 Modification methods

Untreated fibres are usually rinsed and dried before use.

Testing different surface treatments on sisal fibres have led to increased tensile strength in fibres and bond between fibres and matrix. The treatments used where hornification, alkali treatment, polymer impregnation with a styrene butadiene polymer and a hybrid treatment combining horrification and polymer impregnation. With all treatments the fibres showed some reduction in chemical compounds like lignin and hemicellulose with led to reduced water absorption capacity, but not enough to affect their mechanical properties. The hybrid treatment proved to be most effective in improving the mechanical properties and the fibre-matrix bond (Ferreira et al., 2015).

Alkali treating Coir fibres in NaOH leads to a clearer and rougher surface than the untreated fibres and gives improved ductility, tensile and flexural strength and compressive stress and strain due to better interfacial adhesion. Too high concentrations of NaOH damaged the fibres leading to a reduction in mechanical abilities (Yan et al., 2016, Gu, 2009).

Treatment with different polymers and epoxy resin on bamboo fibres show ductile behaviour in reinforced columns and that the treated fibres gave almost the same strength under axial and transverse loading as steel fibres (Agarwal et al., 2014).

# 3.3 Binders, additives, admixtures and fillers

## 3.3.1 Binders

### Coal Bio Ash

Coal bio ash (CBA) is a by-product from power plants that has reorganized from coal to biomass. Defined by (Nina M. Sigvardsen, 2019):

> “This results in new types of fly ashes, e.g. coal bio ash (CBA), where low-alkali coal fly ash (CFA) is injected to the boiler furnace during incineration of wood pellets to hinder corrosion and maintain the necessary thermal efficiency of the fuel.”

Particles are by size to consider as a filler, shapes are both spherical and irregular, and the consistency in the mortar improves due to the high number of small particles. Study by Nina M. Sigvardsen, compared CFA and CBA, and concluded that CFA is a better filling material between the cement particles in the mortar, but CBA contain more calcium oxide (CaO) and expected to conduct as a pozzolan additive, and the study was based on cement replacement.

Compressive strength was lower for CBA than CFA after 14 days, but this changed after 28 days when CBA showed same strength as control specimen of OPC, and much higher than CFA. After 90 days of curing the CBA showed remarkably better compressive strength than both control sample and the CFA, even if also CFA exceed the theoretical activity coefficient. Test concludes that CBA has a higher reactivity due to the material physical properties, and pozzolanic reactions, which both contribute to increased compressive strength (Nina M. Sigvardsen, 2019).

### Rice Husk Ash

Rice husk ash (RHA) can partly replace cement in the mortar. Compressive strength after 28 days showed best results in a mixture of RHA of 50 wt% with w/c-ratio of 0.4 where c is RHA+PC (Stroeven et al., 1999). By full replacement of cement, studies have shown optimal combination of 30 % RHA, 28 % Palm Oil Fuel Ash (POFA) and 42 % slag, the compressive strength was only 7 % lower than OPC, but flexural strength was reduced by 26.9 %. The mixture is dependent of NaOH as binding agent (Karim et al., 2013).

#### Other binders

Studies of eggshell waste, seashell fragments and porcelain grés tiles showed that wastes from brick factories had pozzolanic properties under certain conditions. Egg shells are similar to limestone in chemical composition, and it was expected to find similar properties, but it did not fulfil the pozzolanic requirements, and is not considered as a suitable alternative for cement (Vinciguerra et al., 2018).

Other interesting materials to be used as a partly cement replacement is palm oil fuel ash (POFA). This is a product from palm oil industry with pozzolanic behaviour (Muthusamy and Zamri, 2014).

### 3.3.2 Additives

#### Bio-Geopolymer concrete

Geopolymer concrete (GPC) is an innovative material, based on replacing all OPC with alkali activated aluminosilicate. The formation of the gel structure in the geopolymer (GP) increases the bonding ability due to the effective contact area. This leads to improved mechanical properties compared to OPC. It shows good strength properties and low creep and shrinkage. It requires steam curing or heat curing process, and cement may be used as additive to make GPC at room temperature (Ali A. Aliabdo, 2016). Other factors for adding cement may be to utilize the free water that is left after the chemical reaction and increase the cohesion. The properties, including thermal gravimetric analysis (TGA), are improved and weight loss rate decreased, but workability is reduced by adding cement. Therefor superplasticizer might be necessary (Ali A. Aliabdo, 2016).

Bio-Geopolymer concrete is GPC with bio-additives, such as tree products, natural sugars or different natural fibres. In an alkali medium, such as concrete, tests have shown interactions between bio-additives and GP may decrease the required curing temperature. When biomaterials are added the GPC, slump test have shown an improvement of the workability, this has been observed in mortars that also includes FA.

Low strength in the bio-GP at an early stage can be understood by the geo-polymerization reaction that increase during curing time. It has been reported in different experimental studies that cohesion between aggregate and matrix was improved by carbohydrates from the bio-additives. Compressive, splitting tensile and flexural strength increased compared to GPC without bio-additives. Combination of bio-additive Terminalia chebula with palm jaggery displayed superior mechanical properties as shown in *Figure 28* (Karthik et al., 2017b).

Powder form of Terminalia chebula, which contains gallic acid esters and carbohydrates that has large number of disaccharides, and palm jaggery as natural sugar were used in study by Karthik et al. Mortar with FA, GCBS and 0.8 wt% bio-additives by the weight of aluminosilicate minerals were added to the mortar. This resulted in a very complex cross-linked polymer structures, more dense binding gel and refinement of the pore structure, which leads to decreased water absorption and porosity. The compressive, flexural and tensile strength in addition of modulus of elasticity were enhanced (Karthik et al., 2017b).

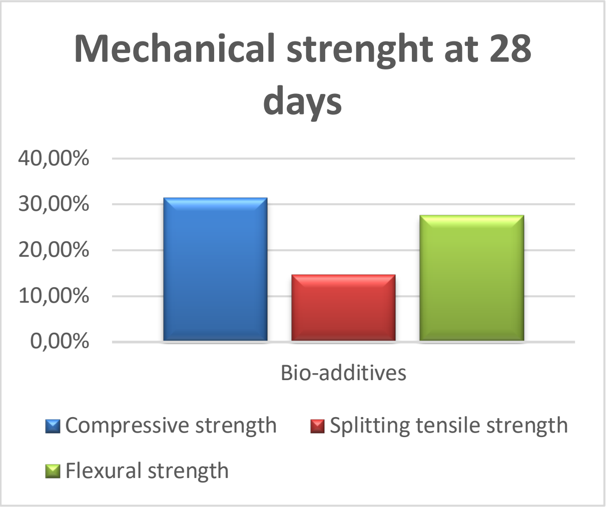


*Figure 28 Improved mechanical properties of Bio-additives Terminalia chebula and palm jaggery, compared with GPC (Karthik et al., 2017b)*

Experiences of bio-GPC for better shielding against chemical attacks and enhance durability have been studied. Especially a combination by Terminal chebula and palm jaggery showed superior durability characteristics when compared to other bio-additive combinations.

Bio-GPC exhibited better resistance to sulfuric acid attack after 90 days and had minimal weight and strength loss under sulfuric, sulphate and chloride attacks than GPC without bio-additives (Karthik et al., 2017a).

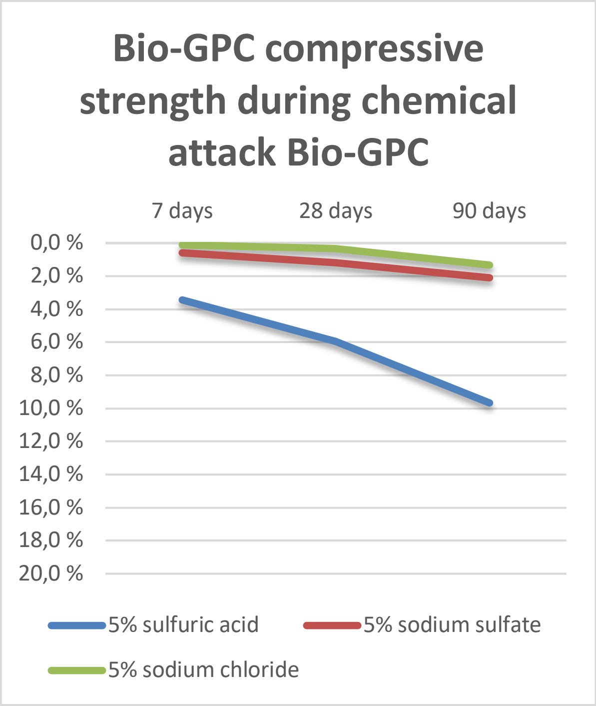


*Figure 29 Bio-GPC, decrease of compressive strength under chemical attack (Karthik et al., 2017b)*

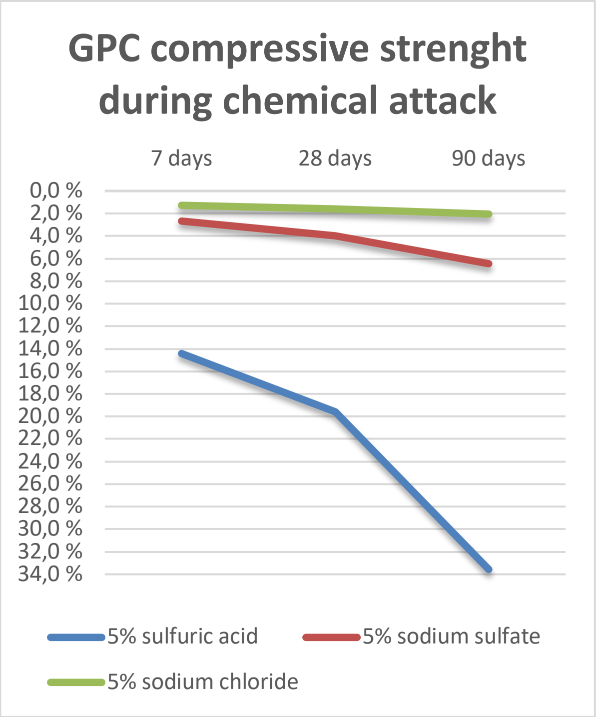


*Figure 30 GPC, decrease of compressive strength under chemical attack (Karthik et al., 2017b)*

#### Naturally reinforced GPC

Geopolymer suffer from brittleness, but by adding fibre reinforcement this can be overcome. Natural fibre reinforced GPC shows low density and enhanced mechanical properties. Addition of 5 wt% (GP) of lignin, cellulose and hemicellulose showed lower density and only slightly lower compressive strength compared with pure GP. By higher hemicellulose or lignin content, reduction in both flexural and compressive strength was observed. In tests arranged by preheating the biomaterial even lower density was measured. When the content of cellulose increased in the mortar, better bonding was observed and fewer pores and a denser structure (Hanzhou Ye, 2017).

### 3.3.3 Admixtures

#### Biochar from food and wood waste

Biochar is generated from waste biomass. It is made by heating the biomass under pyrolysis by 3-700 degrees Celsius. All the non-carbon materials will be burned and what remains is pure carbon. The process produces about 40 % biochar from the total biomass. The characteristics of the biochar depends on type of biomass used, especially the size and shape vary, but all kind of biochar has a brittle and porous structure.

Sugarcane bagasse ash (SCBA) is an indirect by-product from sugarcane industry, where sugarcane bagasse is recycled as biofuel within the sugar mill (Parisa Setayesh Gar, 2017). Other types of biochar are based on food waste (FWBC), mixed wood saw dust (MWBC) or rice waste products (RWBC). Biochar made of rice components need higher temperature in the pyrolysis process, up to 5-700 degrees Celsius for 45-60 minutes. Content of carbon in the RWBC is therefore lower than compared to other biochar products (Gupta et al., 2018a).

In the mortar paste with 1 wt% biochar it was observed increased density in the C-S-H gel compared to mortar with only OPC. Fresh biochar added to the cement mortar showed reduction in the initial setting time and improved compressive strength at an early stage. Improved cement hydration was explained by the porous structure of the biochar.

Biochar from food wastes showed less porous structure than the ones made from wood, and due to more CH crystals and ettringite in the pores the hydration was lower. Therefor it has been concluded that FWBC gives lower strength than MWBC in the initial phase, when 1 wt% was added. Addition of 2 wt% FWBC in the mortar, showed more porous structure not well crystalline. Compared with plain mortar, the 2 wt% FWBC increased late sorptivity by 2.2 times (Gupta et al., 2018a).

Test samples of Sugarcane Bagasse ash (SCBA) show different results, and the workability was reduced slightly and setting time was longer than compared with OPC and also compared with other biochar samples.

All mortars that include biochar showed lower flowability than control sample, and MWBC showed the lowest flowability (Gupta et al., 2018a).

Wang et al. did research on biochar made under different temperatures. MWBC made under pyrolysis of 500 and 700 degrees Celsius showed highly increased compressive strength up to 16 %, when 1 wt% was added in the mortar (Wang et al., 2020). Tests concluded that above 5 wt% MWBC or FWBC in the mortar, the compressive strength was remarkably reduced, due to formation of microcracks under pressure.

Addition of biochar result in higher ductility, however flexural strength was not remarkably improved (Gupta et al., 2018a). Flexural strength is dependent on the type of food waste the biochar is made from. A 42 % increase was given in one test on hazelnut shell biochar (Khushnood et al., 2016), when biochar from coconut shell showed reduced flexural strength .

In lightweight concrete, SCBA above 5 wt% has shown improved mechanical properties (Wang et al., 2020). Good results of compressive strength was shown by replacement up to 15 wt%, but highest increased compressive strength by replacement up to 10 wt% as shown in *Figure 31.* The reaction SCBA showed as a cement replacement, was associated with pozzolanic actions (Parisa Setayesh Gar, 2017).

Due to reduced permeability in the cement mortar and reduced heat in hydration process some test results shown increased resistance against chloride environment. Rapid Chloride permeability test (RCPT) showed a remarkable reduction of 74 % in the electrical conductance when testing 15 wt% SCBA after 28 days, and even higher after 56 days, 83 %. Samples with 25 wt% showed same result already after 28 days but had no further evolvement after 56 days (Bahurudeen et al., 2015).

Due to more porous structure, the bagasse ash increases the permeability ratio of the concrete. Low-weight concrete containing 25 wt% SCBA has shown air permeability of 156 %, when the sorptivity did not change in any specific direction (Bahurudeen et al., 2015).

### Biochar and curing by $CO_2$

$CO_2$ curing will improve the strength in the internal bonding in the mortar, due to the acceleration of carbonation. In the test, MWBC 2 wt% was added and then by curing the test blocks by $CO_2$, had a positive effect on the hydration and carbonation process, and enhanced the strength of the concrete blocks. It was used 0.65-0.70 wt% superplasticizer in the mortar (Wang et al., 2020).

It was observed a significant increase in compressive strength after 7 days in the biochar samples with absorbed $CO_2$. After 28 days the flexural strength was reduced. Closer investigations showed higher hydration by more calcium hydroxide in the paste. It has been shown that initial setting time has been reduced, due to significant reduction of water penetration and sorptivity (Wang et al., 2020).

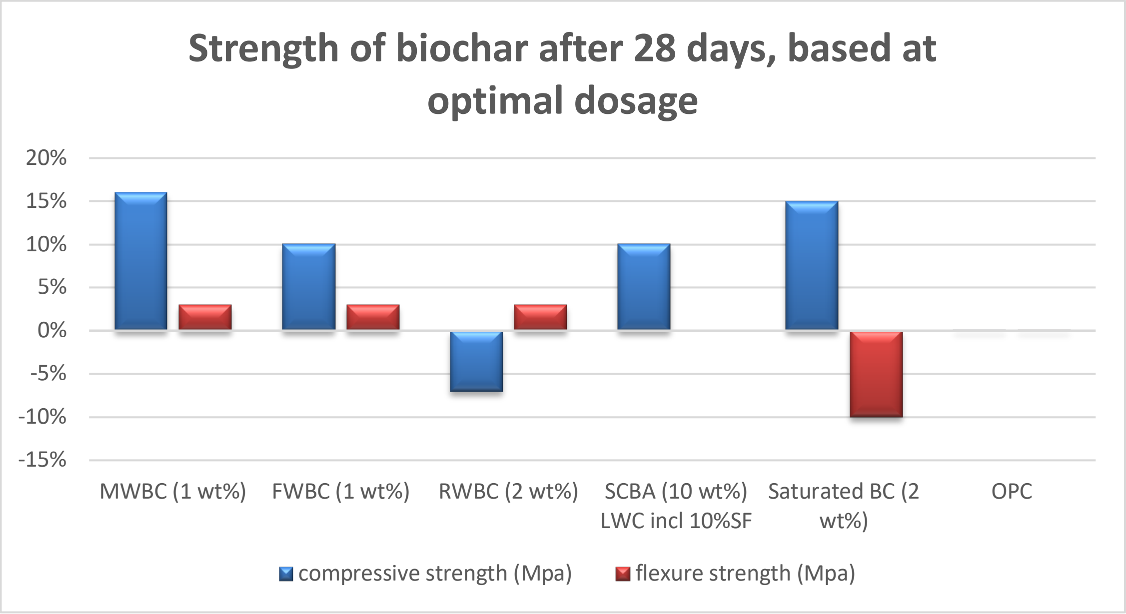


*Figure 31 Strength of biochar based on optimal dosage, w/c 0.4, OPC as control sample, MWBC, FWBC, RWBC (Gupta et al., 2018a), SCBA(Seyed Alireza Zareei, 2018), saturated BC (Gupta et al., 2018b)*

### Biochar with activated Carbon

Activated carbon is normally carbon from an organic material, produced by physical or chemical activation. There are several subcategories under activated carbon.

Studies have shown that without influencing the density and maintaining the integrity and compressive strength, the limit of max 12 wt% can be added in the mortar, while activated biochar can be added up to 30 wt%. Plasticizers will be needed due to reduction in the workability.

Thermal conductivity between 0.192-0.230 W/mK and sound absorption effects have been observed in tests (Nina M. Sigvardsen, 2019).

### Rice-husk-based superplasticizer for GPC

A research aiming to improve flow behaviour of GPC without adding commercial chemical superplasticizers and without compromising the required mechanical strength, made a rice-husk-based superplasticizer specially developed for GP systems. Results show that higher dose of superplasticizer equals better workability and compressive strengths by using dosage of superplasticizer between 0.25 and 1.0 %, however, concerning compressive strength, there was an optimal value of addition of 0.5 % with respect to FA (Chouhan et al., 2018).

### Starch

There are different types of starch utilized as admixtures; cassava and maize.

Research investigating the use of starch as an admixture for improving the physical and mechanical properties of concrete shows that the presence of starch result in increased setting time and reduced workability of the fresh mix. In addition, starch led to improved strength, durability and modulus of elasticity, as well as reduced shrinkage and decreased deformations (Oluwabusayo et al., 2019, Akindahunsi and Uzoegbo, 2015, Akindahunsi and Schmidt, 2019, Akindahunsi, 2019).

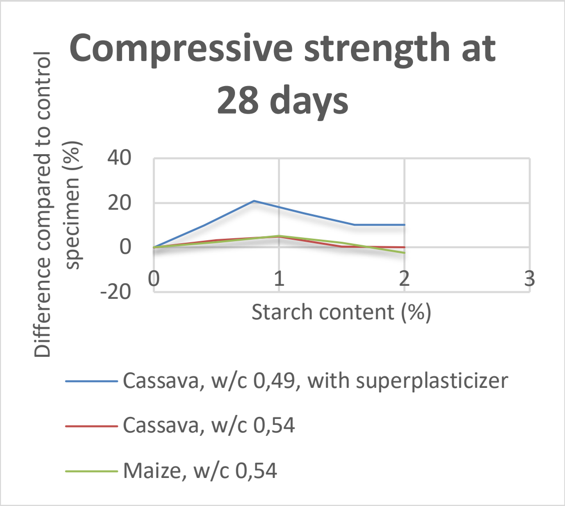


*Figure 32 Starch, compressive strength, w/c 0.49 (Oluwabusayo et al., 2019), w/c 0.54 (Akindahunsi and Uzoegbo, 2015)*

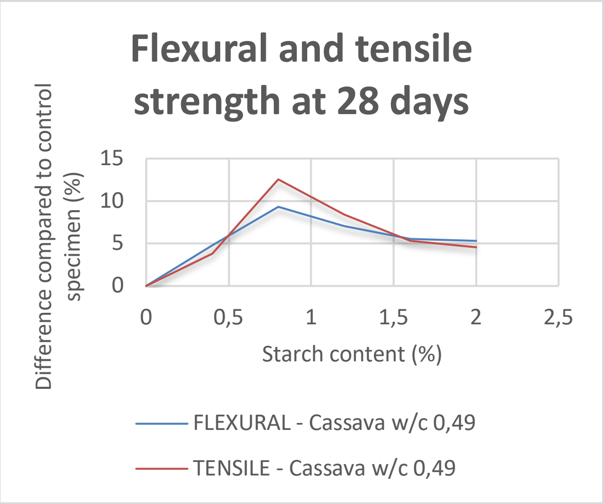


*Figure 33 Starch, flexural and tensile strength, (Oluwabusayo et al., 2019)*

The effect of different starch-based admixtures on cement hydration have been examined. Among the promising results are a corn-starch-based temperature rise inhibitor that allows control of the heat released from cement hydration while maintaining the mechanical performance in the long term. It has a depressing effect in the solid state and a retarding effect in the pre-dissolved state.

Another starch-based chemical admixture (SA) has successfully controlled the maximum heat release rate of cement hydration, which reduces the risk of cracking. However, increased volume of admixture delayed the setting time of the concrete (Yan et al., 2020, Zhang et al., 2018).

### Gum tree lignin

Gum Arabicum is a polysaccharide from various species of the Acacia trees. It is a sulphated lignin with good water solubility and low reactivity with most minerals. The product is mainly used by the food industry as a stabilizer.

The study by Mbugua was based on Gum Acacia Karroo (GAK) which comes from a species that grows wildly in southern part of Africa, and within reach for most African consumers. GAK was used as admixture in its natural form, without any form for processing before use, except dissolved in water for one night (Mbugua et al., 2015).

Tests showed that there were minimal changes in the cement mortar after 28 days for test species with w/c-ratio of 0.5 but showed increased compressive strength in w/c-ratio of 0.4. The best result was achieved by 0.8 wt% of cement. This was explained by the water reduction effect GAK shows in concrete, when polymer chains of cement absorb GAK and precipitation of minerals in the mortar. The sorptivity was improved compared to the untreated concrete sample. This gives increased rate of initial setting time. The best results were shown by sample with 0.8 wt% GAK which had 110 min delayed initial time and 264 min delay in final setting time compared with control sample with PC.

The positive influences on the compressive strength and reduction the rate of hydration results in a denser microstructure. TGA showed that all test species with GAK had less weight loss than control sample (Mbugua et al., 2015).

### Egg - broiler hen

Eggs are not a new material when it comes to constructions. Ancient times used egg whites as bindings in the mortar, and it was widely used to produce paint binder (Neeraja, 2016). There are three components to be used from eggs; egg white, yolk and eggshell. The liquid parts need to be lyophilised before used as admixture in concrete.

In relevant tests, the broiler hen egg went through lyophilisation, then added water and used as natural admixture (NAD). Mortar with NAD mixed with cement and FA forms C-S-H gel by generating the hydration process. The binder sets very fast by addition of a certain amount of NAD, due to the calcium content in the egg which accelerate the hydration and the setting of the binder. This process develops the strength.

The best results were given by replacing 55 % of cement by Fly Ash, where 0.25 wt% was NAD. The compressive strength was significantly increased in the early age, and after 28 days the compressive strength was respectively higher compared with 0% NAD added. Splitting tensile strength and modulus of elasticity did improve for all FA mixes by addition of 0.25 % NAD (Neeraja, 2016). The density is lower in FA and NAD concrete, than pure cement mixtures. By higher NAD dosage than 0.25 %, the NAD film causes delay in the hydration. It has been observed that NAD increases the consistency up to 1 % replacement of fly ash.

### 3.3.4 **Fillers**

#### Eggshell powder (ESP)

The eggshell has a different chemical consistency than the soft parts of the egg and will not react with water and form C-S-H in the same way and does not develop strength. ESP are therefor considered as filler and can replace fine sand in the mortar.

Studies of the radioactivity shielding performances in mortar with OPC, water, sand and ESP showed positive results. Egg shell dosage wt% by mass of sand was used. During test the samples were kept in 10 % sodium sulphate solution from 7, 28 and 90 days. Flexural, compressive and tensile strength was reduced by increase of ESP dosage in the mortar, which is explained by change of the microstructure where the eggshell has poorer bindings in the interface. The test samples including ESP have been found to increase the radiation absorption coefficient (Binici et al., 2015).

D. Gowsika showed in tests that cement replacement of 20 wt% microsilicia + 5 wt% ESP can be added without reduction of the compressive strength compared with OPC. At same amount of ESP but only 10 wt% of microsilicia, tests showed similar flexural tensile and slightly lower split tensile strength and compressive strength than pure OPC samples. It was therefore concluded that ESP can be used as partial replacement for cement with remarks of less workability. The density of the concrete and both compressive and tensile strength will decrease aligned with further increasing amount of eggshell powder (D. Gowsika, 2014).

### Rice husk ash

In addition to being a cement replacer, observations have showed that fine particles of biochar from Rice husk may be successfully used as filler, and may improve density and internal curing (Gupta et al., 2018a). Results show significantly improved mechanical performance when use of Rice husk ash (RHA) as reactive filler. Test conclude it may be alternative for high strength concretes (Sung-Hoon Kang, 2019).

### Nano materials

It can be seen an increasing interest to use cellulose nanomaterials as fillers and reinforcement in concrete. Test have shown higher elastic modulus while maintaining the same water-to-powder ratio. The most common type of nanocellulose are cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs), micro fibrillated cellulose (MFCs) and cellulose filaments (CFs). In the case of the nanocellulose, promising results have been presented. Barnat-Hunek and partners investigated nanocellulose from apple and carrot in the form of nanocrystals and nanofibers. Generally, they found that higher compound of nanocellulose in the concrete lead to increased tensile strength in bending. The highest level was exposed in the apple nanofibril cellulose with an increase of 34.5 %. The compressive strength tests in this investigation revealed that the concrete with 1 wt% nanocellulose based on carrot showed the best result with an increase of 37.9 % in compressive strength (Barnat-Hunek et al., 2019).

Cellulose filaments (CF) are cellulosic fibrils with nanometric diameter (30– 400 nm). CF contains mainly cellulose, about 95%, and a small amount of hemicellulose. Hisseine et al. explored a flexural capacity enhancement at 20 % compared to the reference concrete with a content of 0.30 wt% cellulose filament. The compressive strength improved up to 26 % with a content of 0.05 % cellulose filament (Hisseine, 2019).

In the case of nanocellulose several studies point at the fact that use of nanocellulose showed more C-S-H-structure formed in the concrete. The C-S-H structure makes the concrete strong and improves the freeze-thaw resistance (Barnat-Hunek et al., 2019, Hisseine et al., 2019).

## 3.4 Aggregates

### 3.4.1 Bio-aggregates in LWAC

#### Wood

Even though the strength declines with the addition of sawdust, the compressional strength is within the required limits for concrete grade 30, and the concrete can be used for structural applications.

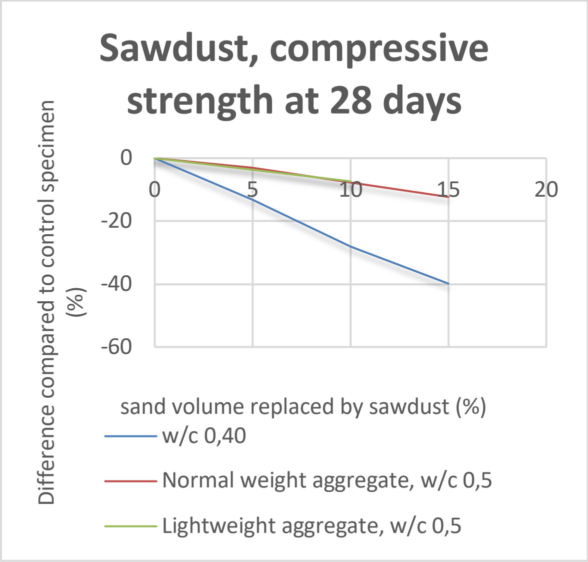


*Figure 34 Sawdust, compressive strength, w/c 0.40 (Suliman et al., 2019), w/c 0.5 (Ahmed et al., 2018)*

Addition of sawdust leads to increased workability of the fresh mix and increased water absorption, but within the maximal allowable water absorption for construction materials. Tests reveal a significant reduction of early shrinkage, increase in the values of rupture strain, improved first crack and total fracture toughness, decreased modulus of elasticity and a considerably decreased thermal conductivity.

The studies also show that the sawdust concrete is free from harmful health contaminants. No form of treatment other than air drying is done before use. The pH values after water curing were within alkali range.

Incorporating sawdust result in low density cement products with improved sustainability and energy efficiency. The low thermal conductivity could improve the energy efficiency of buildings. One study shows 22 % reduced HVAC energy and 13 % reduced $CO_2$ emissions (Suliman et al., 2019, Ahmed et al., 2018, Al Numan and Ahmed, 2019).

Wood waste can also be used as coarse aggregate. Test results have revealed that with up to 25 % replacement of coarse aggregate with wood, the compressive strength meets the strength requirements for reinforced concrete. Tensile and flexural strength follow the same pattern.

Durability studies show that wood aggregate concrete is more susceptible to degradation under acid attack, but at 15 % replacement the concrete is able to contain an alkaline attack. There was no degradation due to fire at this level of replacement. Workability is also improved (Fapohunda et al., 2018).

Saw dust ash produced from incineration of wood and biomass wastes is shown to reduce workability and increase setting time, hence it can be used as a retarder. It also gives good durability properties (Fapohunda et al., 2018).

### Sunflower and corn

Testing performed on multiple samples with different cement contents and w/c-ratio result in decreased slump values, decreased strengths and increased water absorption.

However, the concrete produced in the study, with two exceptions, can be classified as structural lightweight concrete when considering unit weight and compressive strength.

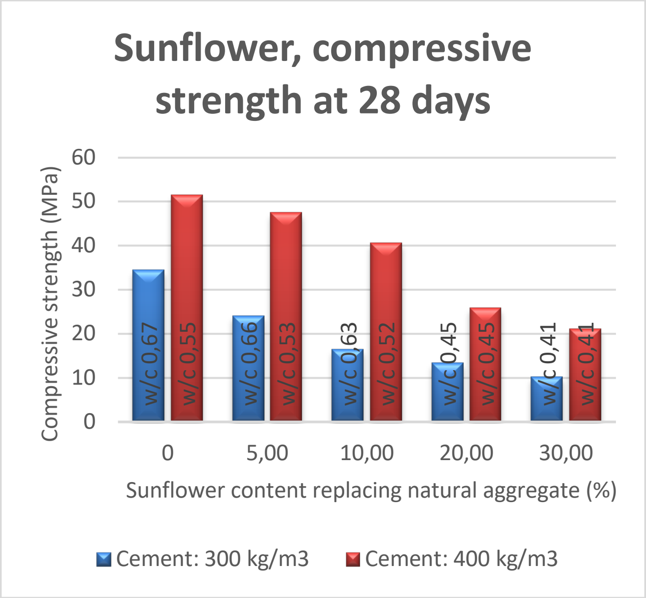


*Figure 35 Sunflower, compressive strength (Sisman and Gezer, 2013)*

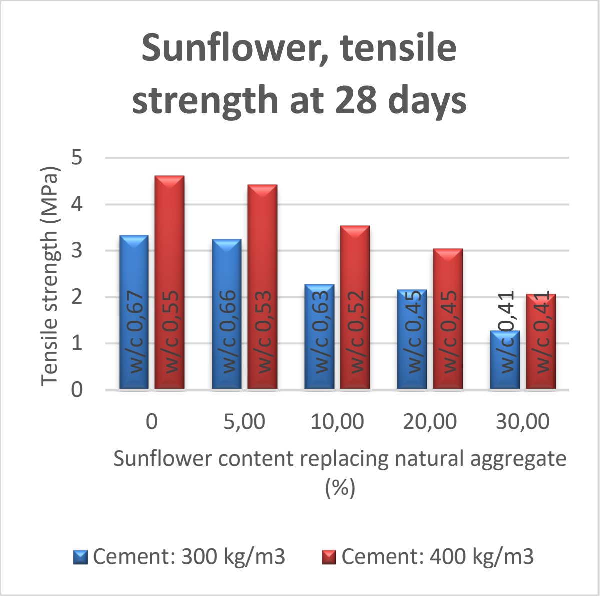


*Figure 36 Sunflower, tensile strength (Sisman and Gezer, 2013)*

The study concludes that structural and insulating concrete can be produced using sunflower seed husk to meet strength, resistance and insulation requirements. This conclusion is in keeping with other research on the subject (Sisman and Gezer, 2013, Chabannes et al., 2015).

Based on earlier studies showing a decrease in mechanical properties when replacing natural aggregates with vegetal aggregates, one study aims to find an improvement. Different mixes were tested with 50 % vegetal aggregates (corn cob and sunflower stalk) treated in sodium silicate solution before use, to reduce their water absorption capacity, 10 wt% replacement of cement with silica fume or fly ash, and addition of sodium silicate and air entraining agent in different volumes. These results show that varying the mix with the mentioned ingredients can alter density, water absorption, compressive strength and splitting tensile strength. In the case of compressive and splitting tensile strength, the best results were obtained with 10 wt% cement replacement by fly ash (Grădinaru et al., 2019).

Another study examining different formulations for maize and sunflower bark bio-aggregate concrete, and two types of binder matrices, based on metakaolin and lime, have found that metakaolin-based materials have better water vapour storage and permeability performances than lime-based ones, and the use of pozzolanic binder matrix is favoured. Metakaolin and sunflower bark chips were most promising combination for designing a hygrothermally and mechanically effective bio-aggregate based concrete (Lagouin et al., 2019).

### Fruit shell in LWAC

Recent studies based on core shell aggregate in mixture with OPC, fly ash and perlite powder can be successfully used in LWAC. Studies used peach (PS) and apricot shell (AS) crushed and carbonized by slow pyrolysis.

The LWAC included carbonized shells both from peach (CPS) and apricot (CAS), showed reduced porosity and the water absorption to less than 10 %. It was observed microcracks in ITZ when used of PS and AS, but no cracks where found by use of carbonized aggregate. It significantly decreased creep strain. Mechanical properties did increase compared to non-carbonized shells as aggregate (Fan Wu, 2018).

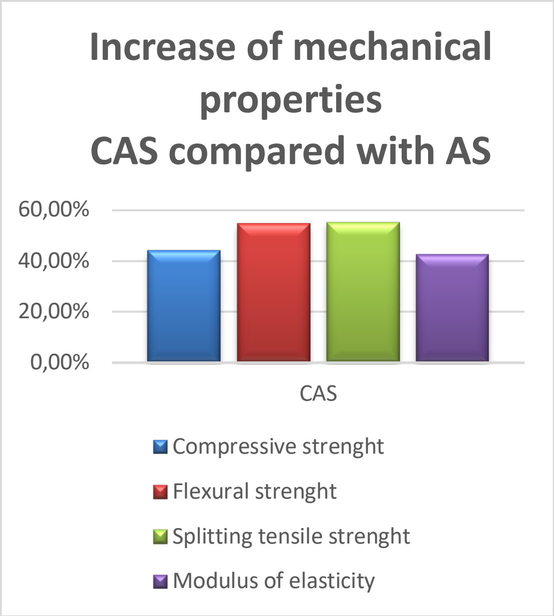


*Figure 37 Mechanical properties CAS vs AS*

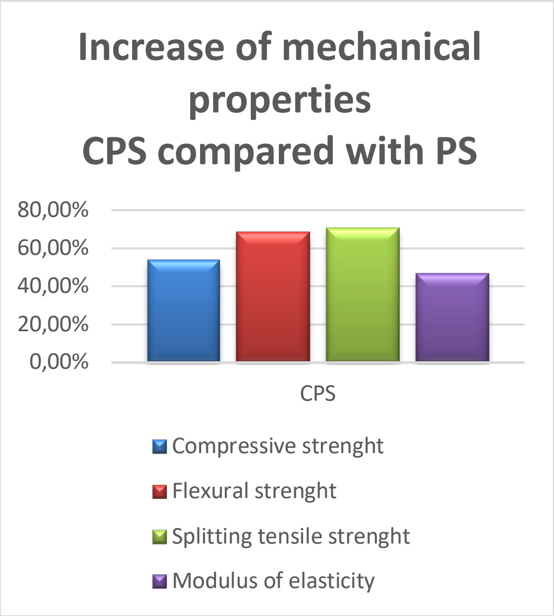


*Figure 38 Mechanical properties CPS vs PS*

Results indicate CAS to be more suitable for production of high-strength LWAC.

Other test used cold bonding method on core shell aggregate, where the energy consumption is much lower than carbonization, also showed promising result of physical and mechanical properties (Feras Tajra, 2019).

### 3.4.2 Recycled aggregates (RA)

#### MDF

A study examining the use of recycled MDF as an organic aggregate in lightweight concrete, resulted in the concrete having highly improved strength properties. After several different treatment methods and methods of preparation, tests showed that saturation in sodium silicate solution and the combined solution of slaked lime and fly ash, proved to be the most effective pre-treatment (the second treatment assumed to be more feasible concerning economical, ecological and technological aspects). The MDF concrete proved to be sensitive to humid environments, with increased water absorption and following strength loss in saturated state and should only be used in dry environments (Malaszkiewicz and Sztukowska, 2018).

### Nano silica and bacteria in recycled aggregate

This method is based on the use of bio and Nano materials for surface treatment of the recycled aggregate from construction and demolition waste. The studies are based on use of two bacillus species, B cohnii and B. megaterium. These are classified as one ureolytic and one non-ureolytic species.

Studies show that water absorption is reduced due to soaking approach of the recycled aggregate, and the density increased. This results in higher workability and improved properties in the recycled aggregate concrete (RAC).

In concrete containing 25 % RAC, observation shows that 3 % Nano silica significantly increased compressive strength, compared with concrete containing natural aggregate (NAC).

The ureolytic species influenced the calcification potential the most, and microstructure showed that pores in both RA and the new mortar were filled and gave a homogeneous RAC matrix. Test concluded that bacteria induced calcite precipitation, which acted as filler in pores and on the surface. Water absorption decreased by 64.2 % (Singh et al., 2018). This resulted in increased compressive strength and durability due to reduced permeability in the concrete (Weilai Zeng, 2018).

### Other bio-aggregates

Among other bio-aggregates that exist and are currently in use or being researched are hemp hurds. Treated hemp hurds as aggregate generally leads to weaker mechanical performance than mineral aggregate, although comprehensive treatment gives better results (Stevulova et al., 2018). Many other plants are considered as aggregates, such as flax and coconut shell.

## 3.5 Self-healing concrete

### 3.5.1 Autogenous healing

The autogenous self-healing process is a natural process of crack repair and is promoted by the presence of moisture.

#### Conventional cement-blends

As reviewed earlier in the paper the main cause of self-healing of conventional concrete is the presence of anhydrous cement. Rajczakowska et.al published in 2019 a study that was based on tests performed on ultra-high-performance concretes (UHPC) and mortar with a low water-to-cement ratio and high cement content.  The UHPC had a w/c-ratio at 0.22 and the other specimens had a w/c-ratio at 0.45. The result in the study strongly indicated that it was not a direct correspondence between high amount of anhydrous cement and self-healing, it could rather limit or even hinder the process. Ultra-high-performance cement has typically a hydration degree at 50-70 %. Three mortar mixes were tested, Ultra-Hight performance cement, ultra-high performance, normal strength mortars based on Portland fly ash commercial blend with approximately 20 % fly ash content. The samples were subsequently exposed by tap water at 20 ˚C for 21 days. The UHPC achieved a mean crack sealing at 0.62 mm. The normal blended cement had a mean crack sealing at 0.64 mm and the normal blended cement with commercial blend of fly ash achieved the largest mean crack sealing at 0.84 mm. The study could not confirm any self-healing efficiency in the ultra-high-performance cement, with a high amount of anhydrous cement. The main reason points on the pore-structure in high strength cement and that lack of interconnected pores limits transport of Ca and Si ions from the concrete to the cracks and hinder further strengthening since the hydration is prevented (Rajczakowska et al., 2019).

#### Superabsorbent polymers

Use of superabsorbent polymers (SAP) is a technique that aims to improve the current autogenous self-healing capacity in concrete. The component serves as a water reservoir when it absorbs and contain the water that enters by the cracks. When the supply of water is reduced, the self-healing period can be extended due to the water reservoir in the SAP`s when the water is released and allow further cement hydration. Furthermore, the SAP has ability to swell and shrink several times, contributing to self-healing over a longer period.

### Crack sealing

An experimental program that focused on the effect of fly ash and SAP on the water discharge obtained at 28 days of healing. Fly ash with a high calcium content has the potential to enable mix proportions with a higher SAP content, in this test it was used a content of 4 m%, 6 m% and 8 m%. The test specimen had a w/c-ratio of 0.45 but the effective w/c-ratio was reduced due to the increasing SAP content without additional water in the mixture. The test showed that specimen containing SAP had a 55 % lower water discharge than for the specimen without SAP`s since the SAP`s transform to an expandable impermeable gel that seal the crack. It is also worth mentioning that the specimen with fly ash obtain finer cracks than specimens without fly ash that improves the damage prevention (Chindasiriphan et al., 2020).

Lee et al. experienced SAP as useful for improving the autogenous crack sealing. The water flow through the samples containing SAP decreased considerable. There was achieved a sealing of a 0.3 mm crack and detected models that suggest that cracks higher than 0.4 mm can be self-sealed with SAP by increased dosage (Lee et al., 2016).

### Mechanical properties

In order to fully utilize SAP as a water reservoir, it is desirable to have a certain concentration and a large sized particle. Additions like this can affect the concrete`s properties and can be crucial.

Sun et al. experienced in their study, when comparing samples with and without SAP, that samples containing SAP with the same curing age had a reduction in compressive strength. Further on, the reduction became more prominent with the increase of SAP as illustrated in *Figure 39*. At the age of 56 days the compressive strength in the mixture containing 1 m% SAP had a strength reduction at 32.4 % compared to the mixture containing 0.25 m% SAP (Sun et al., 2019).

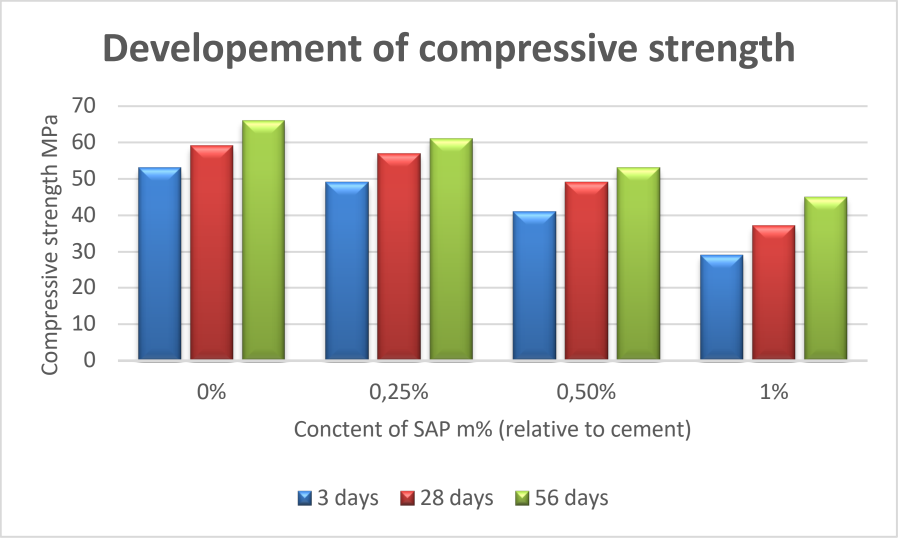


*Figure 39 Comparison of compressive strength in concrete containing SAP*

A key point in this study that is worth mention is that both compressive and flexural strength had a reduction compared to the reference mix without SAP. For specimen containing 0.5 m% SAP at 120 days the test result showed reduction at 30–36 % in the compression strength and a reduction at 23-40 % in flexural strength compared to the specimen without SAP. The highest compressive and flexural strength was achieved by water curing in the concrete without SAP. The authors recommend smaller sized SAP particles in future investigations. The SAP particle in this test had a median particle size about 250 µm. The specimen had w/c-ratio of 0.30 and 0.35 (Sun et al., 2019).

Juntao et al. also investigated the SAP`s impact on the compressive strength in concrete. The content of the SAP investigated was 0.1 m%, 0.2 m% and 0.3 m%. Two sizes were investigated, particles from 250 to 425 µm to 150 to 180 µm. The smaller sized SAP particle was revealed as an optimum particle size range to improve the compressive strength of concrete. This SAP particle size showed an increased compressive strength at later age and has about the same compressive strength as the reference concrete cured under high humidity conditions (Juntao et al., 2017). Another study points to adding calcium nitrate to depresses the initial swelling SAP which allows a higher SAP content without affecting the strength to such an extent. The investigation had a large content of SAP and the study revealed a loss in compressive strength by SAP addition at 5 m% and 13 m% at respectively 87.1 % and 87.4 %. There was not a significant lower value between the two contents due to the depressing effect of the calcium nitrate (Lee et al., 2016).

The loss in compressive strength in concrete containing SAP is as seen validated through several investigations and can be explained with the SAP voids that occurs due to the initial swelling of SAP. In contrast, some studies report an increase in the strength that can be attributed to a lower w/c-ratio, densification of the pore structure that improves the curing and that SAP mitigates the development of microcracks because of the autogenous shrinkage (Chindasiriphan et al., 2020).

A study regarding biopolymer containing alginate beads present a bio-based alternative to synthetic SAP. Alginate is extracted from algae. The study used calcium alginate and sodium alginate as a biopolymer. The calcium alginate exhibited a high absorption capacity and showed an uptake at 67 % and 169 % times its own weight at a relative humidity (RH) at 60 % and 90 %. Sodium alginate exhibited a maximal moisture uptake capacity of 78 % of its own weight. Regarding to accommodate the challenges with decreased compressive strength in concrete containing SAP the study showed a 15 % decrease at a 1 m% addition with calcium alginate -SAP and a decrease up to 28 % for 1 m% addition with Sodium alginate - SAP. The test regarding synthetic SAPs resulted in a compression strength reduction from 22 % to 56 % in this study. The particle sizes ranged from 2 to 85 µm for Sodium alginate and from 2 to 101 µm for calcium alginate and the w/c-ratio were at 0.5 (Mignon et al., 2017).

### Fresh properties

SAP absorbs water and when incorporating them into the cement mixture the concrete`s flowability will be reduced. Generally extra water is needed to ensure the workability. Sun et al. tested the flowability in their thesis. The results showed a linear relationship between the content of SAP and extra water needed to sustain flowability (Sun et al., 2019).

In addition to the particle size of SAP Juntao et al. also explored if the way the water was entrained in the SAP could impact the concrete`s workability. Three ways of water entrainment were tested: SAP without water absorption, pre-absorbed internal curing water and pre-absorbed SAP with the deduction of internal curing water from mixing water. The results showed that pre-absorbed SAP can increase the workability. On the other side the mixture containing SAP without water absorption and the pre-absorbed SAP with the deduction of internal curing water from mixing water shows a decrease in the workability (Juntao et al., 2017).

A study that investigated the combination of fly ash and SAP showed that fly ash had a positive effect on the workability and can thus possibly compensate some of the SAP`s less desirable influence on the workability. It was reported that the water in the mixture changed the SAP into an insoluble gel with an adhesive effect. In addition, the SAP adsorbs free water and produce a lower w/c- ratio in the concrete. It was confirmed a relation between a decrease in the workability with increased SAP content. The authors suggested adding concentrated Ca2+ to the admixture to suppress the water absorption from the SAP`s as a possible solution (Chindasiriphan et al., 2020).

### Cost efficiency

At present the SAP technique is relative expensive and puts limits for commercial use. Lee et al. points on this in their conclusion and pronounces that:

*"At present, the relatively high dosage of SAP required for crack sealing will probably limit its practical application due to cost implications and the undesirable effect on strength" (Lee et al., 2016).*

### Exposure condition

Access to water is a key point in the autogenous self-healing process and it is therefore relevant to explore how different exposures could impact the self-healing capacity. To get an overview two studies regarding exposure and addition of crystalline admixture have been reviewed. Cuenca and Ferrara tested steel fibre reinforced concrete with a w/c-ratio at 0.5. The samples were exposed to either one of the following conditions: tap water, air exposure and wet/dry cycles (Cuenca and Ferrara, 2020). The other study investigated water immersion, water contact, humidity chamber and laboratory conditions as exposure conditions. The samples was fibre-reinforced concrete with w/c-ratio at 0.45 (Roig-Flores et al., 2015). The impact of crystalline admixture was a part of both investigations since adding crystalline is pointed out as favourable to the self-healing process. Crystalline admixtures (CA) is a chemical compound and a hydrophilic material that bond to $H_2O$. The material increases the density of calcium silicate hydrate (C-S-H) and/or increases resistance to water penetration (ACI, 2010).

The investigations revealed following findings considering crack sealing:

- The exposure condition and the initial crack width are the most important factors for crack sealing. The highest crack sealing was observed for the samples immersed in water, the lowest for the air-exposure
- The smallest crack widths corresponded with the highest values of crack sealing.
- The effects of crystalline admixtures were more relevant for less favourable healing conditions, such as open-air exposure and wet/dry cycles.
- It was observed a more stable crack sealing rate in the samples with crystalline admixture and crystalline admixture tends to improve self-healing of concrete for larger cracks.

### 3.5.2 Autonomous healing

The autonomous self-healing process is based on additives as carriers and healing agent to promote crack healing.

When adding new elements to the concrete mix the mechanical properties can change. When incorporating capsules in the concrete it has been experimented loss in compressive strength that is essential to maintain as much as possible. Du et. al investigated how different sizes and types of shell material on the capsules could impact the compressive strength in the concrete. Some of the significant data that was reported is rendered in the following table. The concrete mixture that was used had a w/c-ratio at 0.5. Different shell materials containing paraffine was used and the healing agent was an organic compound, toluene-di-isocyanate (TDI). It is showed that the mixture with the smallest microcapsules had a significant increase in compressive strength at 28.2 % compared to the control specimen without microcapsules. The larger sized capsules had a decrease in compressive strength. This is due to the reason that appropriate size of microcapsules could fill the pores in the concrete and that larger sized capsules enlarges the pores and reduces the compressive strength of the concrete. The largest capsules consisting of nano-SIO2/paraffin/PE wax composite shell had a self-heal capacity between 0.28 mm and 0.48 mm in mortar within 4 hours (Du et al., 2020).

*Table 1 Compressive strength in concrete with incorporated microcapsules*

| | **Average particle sizes** | **Compressive strength MPa** | **Difference in compressive strength compered to reference specimen** |
|---|---|---|---|
| **Microcapsule with particle size 30 to 300 µm** | 90 µm | 39.1 | 28.2 % increase |
| **Microcapsule with particle size 100 to 800 µm** | 320 µm | 29.6 | 2 % decrease |
| **Microcapsule with particle size 100 to 1100 µm** | 480 µm | 28.6 | 6.2 % decrease |

### Microbially induced calcium carbonate precipitation (MICP)

Biomineralization is a process when living organisms produces mineral through biological activity. In the concept of self-healing concrete, the interesting biomineral is calcium carbonate ($CaCO_3$). This mineral formation is compatible with concrete and is therefore suitable to regain water tightness and strength. Both bacteria and fungi can precipitate calcium carbonate through the biomineralization process when an external calcium source is present. To develop the self-healing concept the microorganism used for this purpose must accommodate the following performance criteria (Bundur et al., 2017):

- They must tolerate highly alkaline conditions (pH 12-13)
- High survivability during the mixing process
- High survivability with limited access to nutrients

Besides surviving the environment that is offered in concrete, the organism must also survive the decreasing space in the matrix which occurs during the hydration process. Several techniques have been tested to increase the efficiency of the self-healing process.

Several studies have reported concerns about the bacteria`s survivability in cement-based materials. This have led to propose different carrier compounds to the microorganisms. These systems consist of immobilizing the microorganisms in a capsule, a porous carrier compound or use of pellets or flakes (Jonkers, 2011, Jonkers et al., 2010).

## BACTERIA

In a bacterial self-healing concept calcium carbonate ($CaCO_3$) can be precipitated by bacteria by different biologically induced mineralization processes - microbially induced calcium carbonate precipitation (MICP). The bacteria self-healing concept has been extendedly studied the last years.

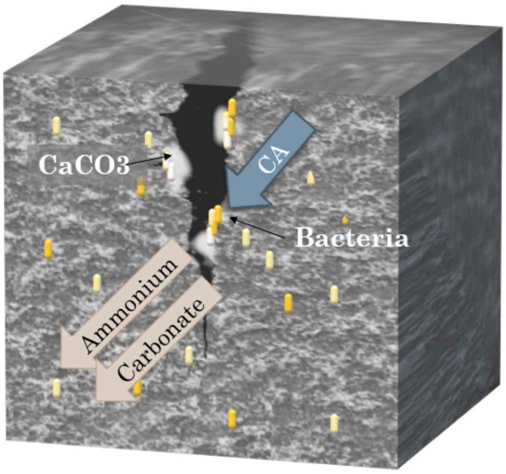


*Figure 40 Bacterial self-healing*

Calcium is essential and the quantity of $Ca_2$+ must be ensured. Further on, bacteria convert the calcium precursor into calcium carbonate like illustrated in *Figure 40.* An encapsulation system mostly includes bacteria spores, calcium precursor and nutrients.

### Crack sealing

Khaliq and Ehsan tested bacteria induced concrete with a w/c-ratio of 0.4 with two different carrier compounds, light weight aggregates (LWA) and graphite Nano platelets (GNP). The bacteria used in this test was Bacillus subtilis. The study revealed that the specimen with GNP had the largest crack sealing with the highest value at 0.81 mm. The largest crack sealing was presented at samples pre-cracked at early age (3 and 7 days). At later days (14 and 28 days) the specimen with GNP as a carrier compound showed significant decrease in crack sealing. Light weight aggregates were not as efficient as GNP at early age pre-cracked specimens but presented a consistency in crack sealing (Khaliq and Ehsan, 2016).

Another carrier compound that has been investigated by Khushnood and partners is recycled coarse aggregate (RCA) with Bacillus subtilis. The w/c-ratio was 0,4. The results revealed that samples with recycled coarse aggregate, bacteria immobilizers and 50% virgin fine aggregate (FA) that was saturated with bacteria suspension to increase availability of bacterial cells inside the concrete exhibited the most efficient crack healing. The largest crack sealing width was 1.1 mm (Khushnood et al., 2020).

Jiang et al. experienced a promising result when they achieved a maximum crack sealing at 1.24 mm after 28 days of healing when using sugar-coated expanded perlite (EP) as a carrier compound. Expanded perlite is a volcanic rock with high absorption capacity. This study used Bacillus cohnii as a healing agent, EP particle size distribution at 2–4 mm and the sample had a w/c-ratio at 0.6. The study experienced highest healing capacity when the expanded perlite was protected by low-alkaline shells, as potassium magnesium phosphate cement (1.24 mm) and acidic sulfoaluminate cement (0.79 mm). High-alkaline shell materials as geopolymer and Portland cement experimented lower sealing effect with respectively 0.39 mm and 0.40 mm. The expanded perlite without a protective shell achieved a crack sealing at 0.27 mm. Mechanical testing was not a part of this investigation (Jiang et al., 2020).

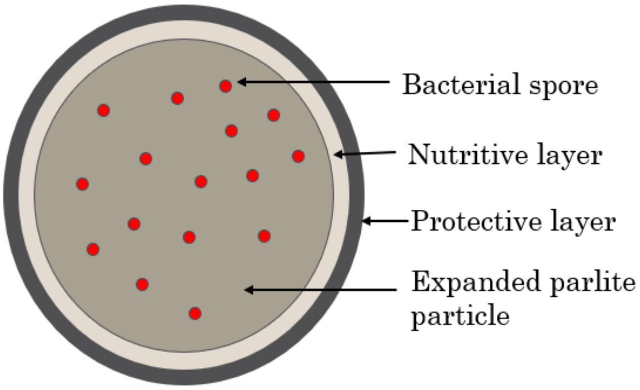


*Figure 41 Expanded perlite particle*

Another study reports a similar crack sealing, with a maximum value of 1.22 mm after 28 days of healing with expanded perlite as carrier compounds. The authors explored aragonite, one of three most common natural crystal forms of calcium carbonite. The majority of the papers regarding self-healing concrete mention calcite, the as the efficient calcium carbonate form. The third common form is vaterite. In this study one non-ureolytic pure culture of the bacteria Bacillus cohnii was conducted beside two microbial consortia, one anaerobic and one anoxic. The w/c-ratio was 0.4. The specimen with the anaerobic bacteria culture and the Bacillus cohnii specimen achieved a crack sealing at respectively 0.73 mm and 0.79 mm. The biominerals in these healing processes was identified as calcite. The crack sealing performed from the anoxic bacteria culture was induced by 82 % aragonite and 18 % calcite achieved the highest value of crack sealing in this test at 1.22 mm as earlier mentioned. The authors point out that this is the highest level of aragonite that is reported to the MICP system at that time (Zhang et al., 2019).

Alazhari et al. proved that also a minimal number of bacterial spores are required to ensure the healing process. Theories has been stated that relatively few bacteria cells are needed initially to achieve efficient self-healing because the cells grow and multiply and leads to an increased bacteria concentration. The concentration of bacteria spores is also of importance when it comes to self-healing in addition of enough calcium precursor available in the concrete. The carrier compound in this study was expanded perlite and the bacteria was Bacillus peudofirmus. The most efficient self-healing was achieved by a ratio of spores to precursor in the order of $8x10^9$ spores per g of calcium acetate (as the precursor) when coated expanded perlite was used as a 20 % replacement of aggregate. This is a higher ratio than earlier studies on the topic. This can be explained by use of different bacteria. The bacteria used in this study may be less efficient in the case of producing calcium (Alazhari et al., 2018). Other studies explicate different suitable spore concentration to other bacteria cultures to achieve a high level of calcium precipitation (Zhang et al., 2017, Wiktor and Jonkers, 2011).

A full-out bio-based self-healing study investigated cellulose fibre as a possible bacteria-carrier. Hight alkali resistant cellulose fibre with an average length at 2.1 mm was used and the w/c-ratio were at 0.5. The bacteria used was Bacillus subtilis. The content of fibres was 0.5 % of the volume of mortar. In the mixture cured with water containing calcium lactate it was observed a healing present at 8.3 % more than the control sample with cellulose fibre. The presence of calcium lactate leads to improved self-healing abilities for all the samples (Singh and Gupta, 2020).

### Mechanical properties

To preserve the concrete properties, it is necessary to investigate compatibility between the healing system and the mechanical properties in concrete. Khushnood et. al reports effects of induced bio-mineralization on tensile properties by an increase in all three different bacteria induced methods that is possible. In concern of the impact on compressive strength it can be seen that in the case of the specimens with direct bacteria incorporation (specimen 1) and recycled coarse aggregate (RCA) bacteria immobilizers and 50 % virgin fine aggregate (specimen 3) the methods have led to an increase in strength. The method with pre-soaking of recycled coarse aggregate in microbial solution (specimen 2) led into 3 % loss of compressive strength associated with weaker contact zone between cement past and the aggregate (ITZ) formed between old and fresh mortar. The increase in specimen 1 and 3 can be attributed to homogenized distribution of bacteria in the matrix as enable uniform deposition of calcite leading to a denser microstructure than in the case in specimen 2. These finding are illustrated in figure 42. The study also tested the compressive strength recovery. The highest compressive strength recovering was 85 % in the specimen with RCA bacteria immobilizers and 50 % virgin fine aggregate. In general, it can be observed that there is a reduction in regained strength with increase in pre-cracking age (Khushnood et al., 2020).

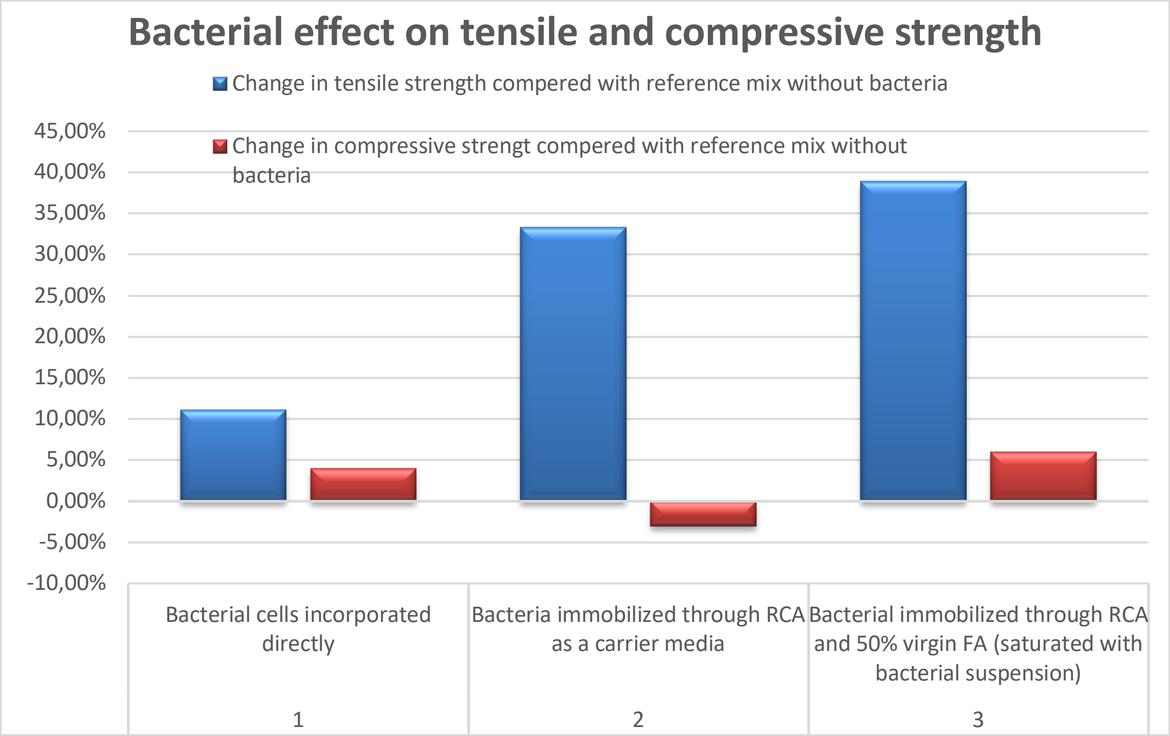


*Figure 42 Bacterial effect on tensile and compressive strength (Khushnood et al., 2020).*

Other types of encapsulation and carrier compounds have been tested to explore the mechanical impact on the concrete. Khaliq and Ehsan rendered that carrier compound of light weight aggregates (LWA) and polyurethane (PU) has shown a negative impact on the flexural strength. Graphite Nano platelets (GNP) showed increased flexural strength in cement based mortar (Khaliq and Ehsan, 2016). A technique that has been patented is sorption of bacteria in diatomaceous earth. The diatomaceous earth has shown no negative impact on the mechanical strength in mortar and even has showed some pozzolanic activity. Hydrogels (mixed SAP) that in addition as a protective carrier also can serve as a water reservoir has also been tested with a significant loss of mechanical strength and further developing to solve that issue has been done. Systems with light weight aggregates as a replacement of sand also resulted in loss in compressive strength (Tziviloglou et al., 2016).

The full-out bio-material self-healing system with cellulose fibre resulted in a compressive strength loss at 33% for samples with cellulose fibres and addition of 4.5 % of cement weight of calcium lactate. The samples with cellulose fibres and water curing with calcium lactate resulted in a compressive loss at 22 % (Singh and Gupta, 2020).

### Survivability

Bacteria that forms spores can survive without nutrients and water for up to hundreds of years. Concrete offers a harsh environment and it is essential that the bacteria can germinate, grow and precipitate calcium carbonate in these conditions. It is reported when adding bacterial spores directly to the cement they remained viable for a period between 2 and 4 months (Jonkers, 2011, Jonkers et al., 2010). Another study has reported viable Sporosarcina pasteurii cells in hardened cement paste specimens as old as 330 days. Based on the results of the review this is the longest survival reported for bacteria in cementitious materials (Tziviloglou et al., 2016). To enhance the self-healing efficiency the self-healing ingredients is been capsuled. Experiments has revealed constantly viability after six months of incorporation (Jonkers, 2011). Several studies report a positive impact on the cell germination and outgrowth of spores when adding yeast extract to the mixture. Oxygen is also a main factor to bacterial growth and spore germination after cracking. Oxygen limitation can therefore be a challenge for aerobic bacteria-based self-healing system spores in the deep part of the crack inside the concrete. Adding nitrate to the system or incorporate an oxygen generator into the system is proposed as possible solutions (Wang et al., 2017, Zhang et al., 2017).

The self-healing system with cellulose fibres also experienced decreasing self-healing at later age, due to the viability of bacteria (Singh and Gupta, 2020).

### Fresh properties

The majority of the literature regarding self-healing concrete has not mentioned the technology’s impact on the concrete’s fresh properties.

### Cost efficiency

The culturing of bacteria needs strictly controlled environment regarding to sterile and antibiotic conditions. This makes the process expensive. Zhang et al. has a possible solution to develop a cost-efficient self-healing system based on bacteria cultures. The study claim that it is economic verified that the self-healing system based on microbial consortia resulted in a

61% decrease in production costs compared to pure culture with promising seal-healing results (Zhang et al., 2019).

Singh and Gupta present cellulose fibre as a carrier compound with a significant cost-reduction with a prize per cubic meter at 14 USD in comparison to both expanded clay and expanded perlite particles with a cost at respectively 111 and 120 USD per $m^3$ of concrete. In addition, cellulose fibres offer water-absorbing properties. The system needs no additional cost for capsulation (Singh and Gupta, 2020).

#### FUNGI

The concept of self-healing technology with fungi spores consist of spores that are mixed in the concrete that waken when favourable conditions occur by cracks. The fungal spores germinate, grow and precipitate calcium carbonate ($CaCO_3$). Fungi can precipitate calcium carbonate by both induced biomineralization and organomineralization processes (Menon et al., 2019). When the crack is totally sealed, water and air supply are also shut, and the fungi will again form spores. Later, the cycle can repeat itself when new cracks arrive.

Fungi can survive and develop in unfavourable environments. Concrete offers a as mentioned a highly alkaline environment in addition to both oxygen and moisture deficiency and it is essential that the fungi can survive and in addition precipitate calcium carbonate. Studies have revealed that some species of fungi has a high survivability at pH up to 13 and contribute in the calcium carbonate precipitation (Menon et al., 2019). It is pointed out that the self-healing system with fungi may be more efficient than bacteria with a more rapid and long-lasting effect. The issue that must be solved is if the fungi spores are larger than the concrete pores the spores will be crushed due to the pore shrinkage during the hydration process. The spores of fungi are usually larger than the bacterial spores. Encapsulation or immobilization of the spores in a protective carrier is a possibility (Jin et al., 2018).

### 3.5.3 Other

A technique that is assessed as a non-direct bio-based is light induced autogenous healing. UV curable adhesive is explored as a healing agent when exposed to long-term solar light radiation. The UV healing agent contributed to about 83.33 % and 68.38 % reduction of the water permeability through the cracks (Lv et al., 2020).

# 4 Discussion

In this chapter we will discuss the overall trend of research regarding the materials that were reviewed in the previous chapter, and if they can be suitable solutions to develop durable and environmentally friendly concrete. The main categories of materials that have been explored is natural fibre reinforcement, self-healing concrete and alternative binders, additives, admixtures, fillers and aggregates. Trough the paper we have been searching for bio-based materials for sustainable material to answer the research question. Materials found is presented in the figure underneath categorized by the UN sustainable development goal we assess it primarily contributes to.

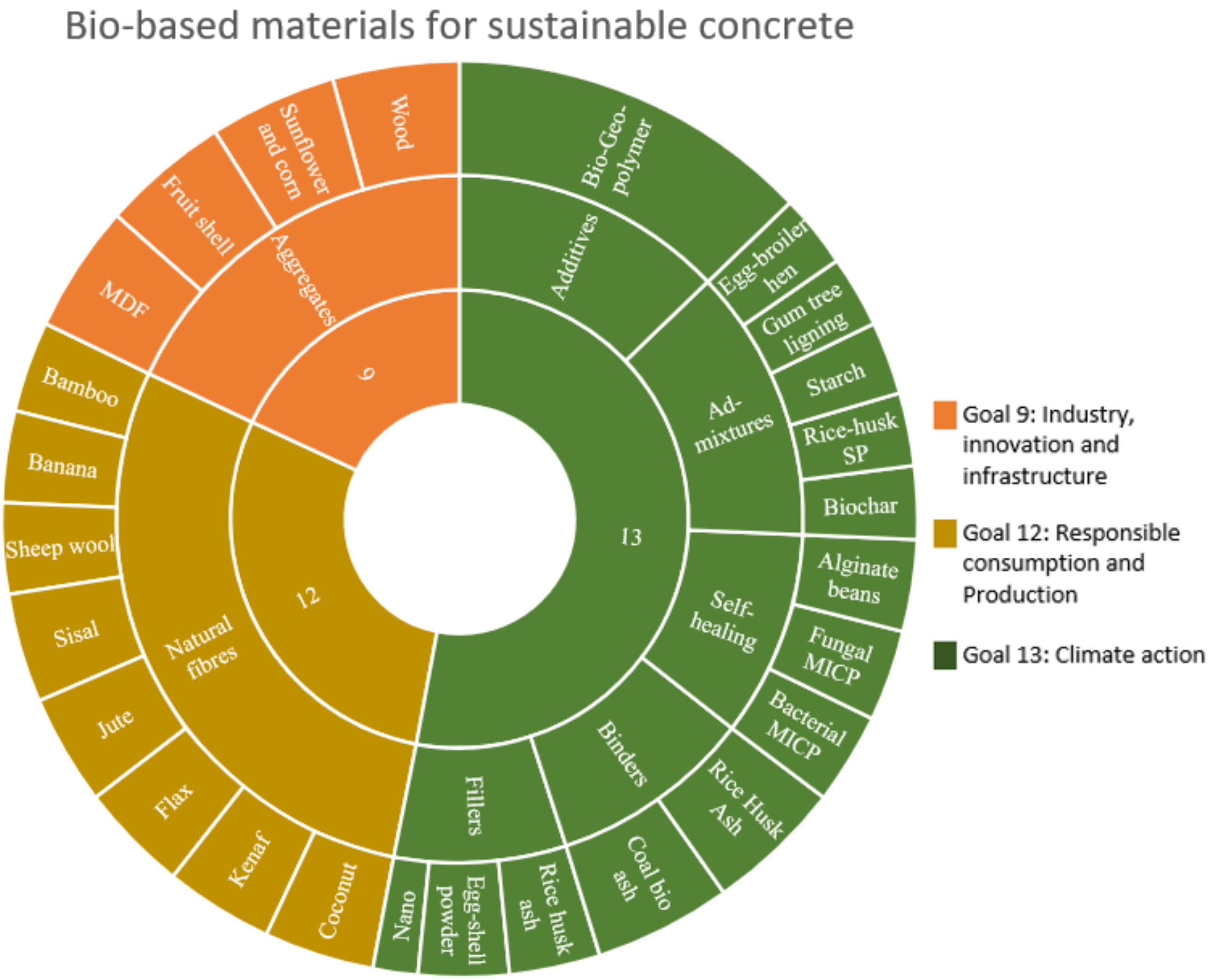


*Figure 43 Bio-based materials for sustainable concrete*

This chapter explores in what way the replacement by sustainable materials can affect the concrete and if it is suitable for commercial production or appropriate to solve other environmental issues without deteriorating the concretes attributes. This chapter will also enlighten the needs of more investigation and innovation to further development.

## 4.1 Natural fibre reinforcement

The use of natural fibres has a long history. Different natural fibres are found all over the world and are available as they grow naturally in the environment. They also require little to no energy to produce, can be extracted from waste material, are economical and low in cost, and can reduce the environmental impact when used in the construction industry. To make use of all these good qualities, we need to know more about how the fibres affect the concrete. Recent studies shed light on how these fibres affect the fresh properties, mechanical abilities and durability of the concrete, and how the properties of the different fibres, combined with the mix design can improve these abilities.

Reinforcement is meant to improve strength and reducing crack formation is one of the main objectives for utilizing fibres in the concrete, when this results in longer life and reduced permeability.

The natural fibres provide an alternative to steel and glass fibres, and also as an addition to un-reinforced concrete. Many of the fibres are easily grown and cost effective. Some of them even exists as agricultural waste already, and in these circumstances using them in concrete production would also serve as a waste reducing measure. Other positive notes are that the fibres are biodegradable and little to no fertilizers are used. The natural fibres are available in large quantities with a continuous supply and can be locally sourced, reducing transport emissions. Most areas of the world have access to natural fibres of some sort, as some of them grow in warm environments, and some in cold.

Two main ways to achieve sustainability in the area of fibre reinforcement are utilizing natural fibres instead of for example carbon, steel and glass, and using industrial waste materials. While our focus is mainly on natural materials, some of the fibres reviewed are also waste products from other industries, which make the environmental gain even better.

### Bamboo

Incorporating bamboo fibres lead to a reduction in compressive strength, and *Figure 6* points to fibre length as an important variable, as the longer fibres had a smaller reduction in strength. On the other hand, the fibres provide excellent flexural and tensile strength to the concrete. *Figure 7* and *Figure 8* shows a comparison between bamboo and steel fibre reinforcement, where the bamboo fibres provided significantly better strength on both areas. This makes for a good replacement for the traditional steel fibres in applications that require tensile and flexural strength and is not dependent on high compressive strength. If we can replace steel fibres with bamboo fibres without compromising the durability of the concrete, this will be an excellent environmental measure for the concrete industry.

### Sisal

*Figure 9* shows varying results from compressive strength tests with the same length of fibres, and points to the importance of w/c-ratio. A low w/c-ratio seems to give better compressive strength, but as mentioned this causes problems with workability. The tensile strength is highly improved up to a certain point of fibre addition *(Figure 10)* and with increased flexural load and modulus of elasticity the sisal fibres can provide good strength properties to the concrete. Since studies have tried different treatments to improve durability of the fibres and not been successful, more research is necessary on this area before the fibres can be utilized.

### Coconut

Of all the fibres researched in this thesis, coconut fibres are of the ones that shows the most promising results concerning compressive strength. *Figure 11* shows almost conclusive results of increased compressive strength up to a certain point of fibre addition. The one study that have decreasing results (w/c 0.48) only measured strength for additions of 0, 1 and 2 % fibres, which means that they might also have had an increase if they tested for additions between 0 and 1 %. It also seems that the longer fibres can keep the compressive strength level with higher fibre additions, and that a lower w/c-ratio gives better strength. The tensile and flexural strength have a very similar pattern to the compressive strength, hence incorporating coir fibres give good strength properties to the concrete in all areas.

The fact that the coir fibres have a slower degradation process than many other fibres, makes it one of the most promising for use in concrete. The durability is of such importance that it cannot be overlooked, and in the case of coir, which has shown to give the concrete improved resistance to both acid and sulphate attack, and good strength properties while wet, it might be sufficient. How the fibres withstand the alkaline environment in the concrete over time is yet to discover and must be explored. The coir fibres are also available as a waste product from agricultural industry and are constantly produced all over the world, which makes it highly available. Utilizing it will reduce energy use and emissions from burning the waste.

### Jute

The Jute fibres are, like coconut, of the fibres that improve the compressive strength of the concrete. In *Figure 13* we can see that jute improved the compressive strength in almost all cases tested. The figure also shows that spun thread gives better results than fibres, that both fibres and yarn give best strength when longer, that the percentage of addition makes a big difference and that the specimens with lower w/c-ratios have the highest compressive strength. *Figure 14* and *Figure 15* shows that both the flexural and tensile strength have similar results. Therefore, concerning strength abilities, jute is a promising fibre to use as reinforcement. Although durability needs more research to conclude good long-term abilities.

### Flax

Flax stands out with having good durability in alkaline environments, in addition of good results from saltwater and hydraulic lime immersion, which makes it a feasible alternative for reinforcement. Although, it is not good in higher temperatures, which must be taken into account when choosing a suitable application. Concerning compressive strength, *Figure 16* shows a pattern: a lower w/c-ratio and longer fibres seems to give higher strength. The flexural strength generally increases but it is hard to spot a connection between strength, w/c-ratio and fibre length *(Figure 17)*.

### Banana

Both compressive and tensile strength have a slight increase with small additions of fibre, but then declines *(Figure 18 and Figure 19).* As the banana fibres show poor resistance, strength and durability when exposed to high temperatures, sulphate, chloride and acid attacks, it does not seem to be suitable as concrete reinforcement. Exploring different treatments might result in improving these abilities. However, the small positive change in strength is not a big enough gain to defend a big effort to make the fibres more durable, as there are many other fibres that show better abilities and thus are more promising.

### Kenaf

As Kenaf has proved to have good adoptability to local conditions, it can be planted in areas that don’t already have usable fibres growing there, and thus make them even more available. *Figure 20* shows that compressive strength is decreased with addition of kenaf fibres to the mix, and that a lower w/c-ratio with longer fibres give better strength. In *Figure 21* we see the positive effect on the tensile strength, with a significant improvement up to 0.4 % addition of kenaf fibre. With this in mind, and the reduction of crack propagation, improved ductility and crack resistance, Kenaf fibres are promising as reinforcement in concrete slabs.

### Sheep wool

Sheep wool shows potential as fibre reinforcement. The improvement in properties from a simple saltwater treatment makes it both cheap and easy to modify. Similar to other fibres it gives decreased compressive strength *(Figure 22)*, however with fibre treatment the compressive strength loss is minimal at small inclusions (under 1%). This makes it possible to make use of the increased flexural *(Figure 23)* and tensile *(Figure 24)* strength for additions under 1%. Although it does not perform as well as many of the other fibres reviewed, it is quite new, and more research may reveal how to better the properties.

The experiments reviewed were done with «regular» wool. As the wool with satisfactory quality is used in wool industry, the concrete industry may need to utilise the wool with the poorest quality (considered as waste) to not compete for resources. In that case new experiments must be done with this wool, as it may not have the same properties as the wool reviewed.

### Other fibres

The many other fibres available show similar results as the ones mentioned. They have not been covered in this thesis due to reasons stated in scope. Basalt differs from the other fibres, as it is a volcanic mineral and falls outside the scope of this thesis. However, it should be mentioned as a promising natural material for reinforcement.

### Summary

The best results from strength testing of each fibre can be seen in *Figure 25, Figure 26* and *Figure 27.* The best results when compared to each experiments control specimen show that jute, coconut, flax and sisal give good compressive strength to the concrete, while banana, kenaf and bamboo don't perform well *(Figure 25).* All these samples have cured under similar conditions, which eliminates the effect different curing conditions is to the result.

The flexural strength *(Figure 26)* is highly improved in all fibres, however bamboo stands out with a significant improvement, making it preferable in applications that require high flexural strength. These studies also have similar curing conditions, which makes the results more credible. The tensile strength *(Figure 27)* is also improved for all fibres, but bamboo stands out here too as an excellent reinforcement for applications that need tensile strength. Although the curing conditions are similar, it is difficult to determine the effect the superplasticiser and silica fume may have had on the outcome.

Most of the tests have different mix designs with w/c-ratios. This is an important variable, that may make the results questionable when we want to compare how the different fibres perform. It would be both interesting and important to compare similar mix designs with the different types of fibre to be able to definitely prove which fibres are most promising in the different areas.

### General similarities

The different fibres all have their own properties, however there are some commonalities. Incorporation of fibres generally leads to lower density and is great for making lightweight concrete. The fibres all lead to increased water absorption and a small to significant reduction in slump values. The increased water absorption may be due to the fibres acting as water-conducting channels which, if exposed to a corrosive environment, will make the concrete less durable. It is important to note that the increased water absorption and following reduction of workability might be possible to avoid by increasing w/c-ratio or with the addition of a superplasticizer. Also, in some cases the workability was sufficient for some applications, even with the reduction of slump value. Different treatments of the fibres can also reduce their water absorption, but this may also lead to changes in other properties of the concrete. If we want to utilize the positive abilities of the fibres, we need more research on how to reduce water absorption.

### Modelling/predictions

Another challenge is that it is hard to predict how the fibres will perform since it is randomly oriented in the concrete, also because of the individual differences between each fibre. Since it is difficult to produce good mathematical and numerical models to predict the mechanical properties lab testing of the properties is of importance.

### Strength

For both flexural and tensile strength it is clear that fibre length and percentage is crucial to the outcome, but this does not seem to be a big problem as it is easy to control fibre length and percentage, and within the limits tested it does not seem to have a negative effect on other abilities. The compressive strength on the other hand has some issues. As it is a clear connection between w/c-ratio and compressive strength, we need to choose between strength and workability. As mentioned, the addition of fibres leads to reduced workability, which can be managed by increasing w/c-ratio, but this will in turn reduce the compressive strength. It would be useful to find a way to reduce the compressional strength loss so that it is possible to utilize the fibres ability to improve the flexural and tensile strength of the concrete. This stands out as a key area for further research regarding natural fibre reinforcement in concrete

### Durability

A main drawback of natural fibres is their sensitivity to environmental conditions such as moisture, which may affect the mechanical properties of both the composite itself and its adhesive bond with the host structure in the long term. There are big differences in the durability of the fibres. Some have poor durability in general, some improve the resistance to sulphate and acid attacks, some reduce it, and some are durable to many different exposures. The coir and flax fibres show some promising durability properties. The coir improved the concretes resistance to sulphate and acid attack and flax to saltwater and alkali water, and the fibres themselves seem to be durable which makes them the most promising fibres in this area. Most of the fibres may need treatment to make them durable enough for use in concrete.

The cost and environmental impact of the treatment needs to be weighed against the gain of using the fibres. There is definitely need for a lot more research on this subject.

### Modification methods

Different treatment methods have shown improved properties in the concrete. One particular problem that might be partially solved by treatment is the fibres good water absorption capacity. Even though the treatments improve the fibres abilities, we need to consider the environmental impact that follows. Working with NaOH can be dangerous, and it is not the most environmentally friendly treatment. Epoxies or polymers aren't either. However, if the treatments have bigger gains than disadvantages, they should be considered. Making the fibres last longer or giving the NFRC a greater range of applications may defend utilizing the techniques. For instance, bamboo fibres treated with polymer might be more environmentally friendly than steel fibres considering they show almost the same strength. Being able to control some of the fibres properties trough treatment is also contributing to increase the possible applications.

Most of the fibres reviewed in this thesis have only been rinsed in water and dried. The treated fibres mentioned have been immersed in NaOH or saltwater. This, because it is important to explore other options before choosing treatments that are not as environmentally friendly.

### Main challenges with natural fibre reinforcement

- Workability issues – having to choose between workability and compressive strength
- Hard to model – time consuming testing to determine outcomes of different variables
- Varying durability – many variables
- Long term durability
- Lacking research

### Main gains with natural fibre reinforcement

- Non-toxic
- Biodegradable
- Little to no pesticides used

- Require little to no energy to produce
- Can be extracted from waste material
- Easily grown and some can even be planted in areas they are not indigenous to
- Available in large quantities, continuous supply, locally sourced
- Cost- effective
- Lightweight
- Increases tensile and flexural strength
- Increased compressive strength for some fibres

### Applications

With the different fibres varying strengths and weaknesses, there are some limitations to which applications they can be used in. Choosing the most suitable fibre for each application is also important.

Since low slump values is an issue with most of the fibres, the concrete might be appropriate for applications needing low-slump concrete, such as roller-compacted roads and foundations.

Focusing only on weight and density, all the fibres are excellent for use in lightweight concrete and can help lighten the dead load of the material.

Where both compressive, flexural and tensile strength is required, both coconut, jute, flax and sisal can be used.

For many cases it might be possible to accept a small compressive strength reduction to get the good effect on flexural and tensile strength that the fibres give. For applications that don’t require compressive strength bamboo and kenaf are good alternatives. Examples are mass fillings, foundations and floors on ground for houses, home driveways and pavements.

Many of the fibres show promising results for confining cylinders and can replace the traditional methods of retrofitting. In this case we might also be able to disregard the fact that some of the fibres might not have as long a life as the synthetic fibres, due to easier replacement at end of life, with the fibres being on the exterior of the construction.

Until long term durability is thoroughly investigated, the fibres can also be used as temporary reinforcement where such is needed.

Because of the fibre’s good thermal insulation properties, they show potential for use in thermal applications, such as passive houses and low-energy houses.

Some of the fibres have been tested and proven to be appropriate for specific applications, such as jute for JFRP and flax for TRM systems. Oil palm and date palm fibres show high energy absorption and ductility and is thus a promising material for seismic applications.

As a big part of fibre applications in concrete are for slabs on ground that need increased tension capacity, incorporating fibres will increase tensile strength and lead to reduced necessary slab thickness and therefore less concrete required.

### Environment and sustainability

The fact that the fibres require little to no pesticides, are energy effective and are easily grown make the production sustainable. Compared to the production of synthetic fibres, which require a lot of energy and contributes to pollution, the natural fibres are a clear winner when it comes to production. The fact that many of the fibres can be extracted from waste materials is also positive. This cuts down energy use and emissions associated with the burning procedure and reduces pollution from landfills.

The fibres can be locally sourced, reducing transport emissions and contributing to local industry. The fact that they are non-toxic makes both production and use safer for the environment and the people working with it.

The biodegradability of the fibres makes them recyclable, which when replacing synthetic fibres limits waste and pollution.

The good availability and large quantities of the fibres means there is no risk of emptying natural recourses.

The fact that the natural fibres may have a shorter life than for instance steel or glass fibre, must be taken into account. The rate of replacement has to be weighed against the benefits of replacing with natural fibres. Natural fibres that could possibly replace steel fibres (mainly bamboo), would lead to a significant reduction in the carbon dioxide emissions and energy used in producing the traditional reinforcement.

With such an improvement of sustainability, some reductions in mechanical properties may be acceptable, at least for some applications.

### Further research

Considering the positive environmental impact of utilizing natural fibres, the value of research on this area is huge, as there are many problems yet to be solved. According to our study, these areas need more research:

- Treatment of fibres. Many of the issues concerning durability and workability may be solved with the correct treatment of the fibres.
- Mix design and strength. The w/c-ratio is an important variable in strength tests, but with this variable being different in most experiments, it makes it impossible to make a definitive conclusion about how the mix design is best customized to achieve the highest possible strength. Even though some fibres have good maximal values in results from strength tests, many have varying results and it is important to figure out what contributed most to the maximal values.
- Good comparisons between fibres. Tests with different fibres where all other variables are similar is necessary. This includes mix design, treatment, curing conditions etc.
- Admixtures and additives. These can possibly help reduce the negative consequences of incorporating fibres, especially concerning workability.
- Long term durability. There is far too little research on long term durability. This needs to be known before we can safely utilize the fibres as reinforcement.

When it comes to which fibres should be included in further research, we would recommend taking a closer look at the most promising fibres, such as jute, coconut, flax, sisal and bamboo. Banana on the other hand has such a small improvement that it may not be sensible to do further work on how to improve its abilities.

To summarize there are many advantages of using natural fibres in concrete, and many challenges to solve before we can fully take advantage of the material.

## 4.2 Binders, additives, admixtures and fillers

### 4.2.1 Binders

The commonly used materials for cement replacement are fly ash (FA), silica fume or slag cement, normally between 15-40 %. The main focus in innovative studies lay at alkali-activated binders, such as geopolymer (GP), which have showed superior durability and environmental impact compared to OPC and may replace cement by 100 %.

#### Coal Bio Ash

Research investigating the use of CBA as binder result in:

- Decreased compressive strength at early stage, but increase after 28 days
- Improved durability
- Pozzolanic behaviour

It is interesting to study ordinary fillers as material for cement replacement. The higher amount of Calcium Oxide (CaO) in CBA increase the capacity to neutralize acid and result in higher buffer capacity than control specimen with OPC, also compared with CFA. The lower strength at an early stage need to be considered against the increased strength after 28 days and it show results above the theoretical activity coefficient after 90 days. This can be explained by the pozzolanic reactions.

CBA is an interesting material and expect to increase in volume when more ordinary coal power plants change to use biomass as fuel. This make the material more sustainable in several levels in the life cycle.

#### Rice Husk Ash

RHA shows interesting properties for further studies as cement replacement in mortar, due to pozzolanic behaviour.

### 4.2.2 Additives

#### Bio-Geopolymer concrete

Research investigating the use of bio-additives in GPC result in:

- Increased workability
- Lower curing temperature in GPC
- Increased compressive, flexural and split tensile strength
- Increased modulus of elasticity
- Better resistance against chemical attacks
- Improved durability
- Lower costs than GPC

Geopolymer concrete (GPC) is an innovative material based on replacing all OPC with alkali activated aluminosilicate. It has high compressive strength, low shrinkage and creep abilities, excellent non-in flammability and exemplary durability. It may be used in a wide range of applications, but on the negative side GPC require steam curing or heat curing process. This is challenging and expensive to handle on a job site, therefor GPC require pre-fabrication. To study the impact that additives have for reduction of requirement of external heat is important to develop GPC to become more sustainable. Cement is normally used in GPC today despite it reduce the workability, and it is of interest to replace this with more sustainable materials, such as bio-additives. Tests show that in an alkali medium, the interactions between bio-additives and GP may lead to decrease in required curing temperature.

All bio-additives showed increased workability and the additives that showed the best mechanical strength was combination of powder Terminal Chebula and palm jaggery.

Combination of bio-additives, FA and GCBS show results of a very complex structure, which can be explained by cross-linked polymer structures, more dense binding gel and refinement of the pore structure. This leads to decreased water absorption and porosity, and the strengths were enhanced as shown in *Figure 28.*

Studies of bio-GPC for better protection against chemical attacks and enhance durability showed improved properties. The combination of Terminal Chedula and palm jaggery did again show the best results compared with other bio-additives. Significantly increased durability, and after 7 days the difference between bio-GPC and pure GPC was shown due to less weight loss and only slightly reduced compressive strength. After 90 days sulphuric and chloride attacks, bio-additive samples had minimal loss in weight and compressive strength compared with GPC as shown in *Figure 29* and *Figure 30*. Based at that study, conclusion is that bio-additives added geopolymer concretes had enhanced durability properties compared to pure GPC. This leads to interest of further studies with this kind of additives.

Fibre-reinforced GPC by cellulose fibres, showed improved properties. All type of fibres showed low density and herewith lower density of the final concrete structure. It has an advantage of low costs and recyclability, but on the other side the interface between organic material and matrix is inconsistent. Organic material may absorb some of the water needed for cement curing. Long-term basis the alkalinity of pore water, may tear on the natural material.

Bio-additives in GPC is an environmentally friendly alternative to OPC due to the reduction of $CO_2$ emissions from the cement industry, which allows GPC to be cured in normal temperatures, and at same time it utilizes waste materials.

### 4.2.3 **Admixtures**

#### **Biochar**

Research investigating the use of biochar admixture result in:

- Reduction in initial setting (not valid for SCBA)
- Improved cement hydration
- Reduced permeability
- Lower flowability, where MW showed lowest flowability
- Improved compressive strength at early stage
- SCBA showed increase resistance against chloride attacks
- Improved durability

Biochar in general showed best effect on fresh mortar and all kinds of biochar showed lower flowability than OPC, due to reduced permeability and heat in the hydration process. We can explain this by the pozzolanic reaction.

Due to higher content of carbon in MWBC than BC from food, it showed significant reduction in total absorption and fluid penetration. Compressive strength increased in all type of BC except RWBC. SCBA showed also promising result of the compressive strengths in LWC. By saturated MWBC by $CO_2$, the mechanical strength improved even more than MW from high temperature pyrolysis. $CO_2$ curing accelerates the carbonation and improve the properties in the fresh cement and showed high increase in mechanical strengths after 7 days. Despite that the saturated BC improved the strengths in an early stage, we find that the final strength was reduced. Flexural strength in FWBC varied, based at type of FW, but were on the other side less porous.

We can conclude from the results that the best amount of BC from food and wood waste is 1-2 wt%, and that MWBC showed best results in compressive strengths by addition of 1wt%. Strength increased by 8-10 % compared with OPC, but amount of MWBC over 5 wt% the strengths were remarkably reduced.

On the other hand, SCBA can successfully be added by larger amount in the mortar for obtain improved mechanical properties. About 10 wt% can be added to obtain the best compressive strength. It is also interesting to find increased resistance against chloride penetration. SCBA showed the best resistance where RCPT showed remarkably reduction of 83 % in the electrical conductance after 56 days.

There are several methods of handling BC, where we studied the two that showed best mechanical results, and that may influence production technology in direction of a more sustainable construction industry. By use of activated carbon combined with BC have shown remarkably building physical properties. By addition of 1-2 wt% improved insulation properties and building energy efficiency have been shown, together with good sound absorption.

It is important to mention that the fresh BC has higher mechanical strengths and improved permeability compared to BC saturated with $CO_2$, and therefor BC may have the potential to be successfully used as a carbon sequestering admixture in concrete. Initial trials show catalytic capacity. The Norwegian cement industry have high focus on carbon capture and storage, and we recommend further studies.

Other environmental benefits can be achieved by use of BC due to reduce landfill disposal for food and food waste products. To increase recycling rate and reduce agriculture waste offers promising environmental benefits and economic incentives. Carbon activated BC increase tolerance of amount of biochar added in the mortar without influencing the integrity and compressive strength, and this contribute to need of less cement and result less greenhouse gas emission from the concrete.

### Rice husk-based superplasticizer for GPC

Seemingly a good admixture alternative to the commercial superplasticizers, such as synthetic polymers. Rice husk is also available as waste from other industries, which makes it cheap and easy to come by.

### Starch

Research investigating the use of starch result in:

- Increased setting time
- Reduced workability
- Improved compressive, split tensile and flexural strength and modulus of elasticity
- Reduced shrinkage and decreased deformations
- Improved durability

*Figure 32* shows that starch admixtures can increase compressive strength of concrete, however low w/c-ratio is necessary for high increase, which will lead to workability issues. The flexural and tensile strength is increased *Figure 33*. The fact that the compressive strength is not reduced makes is suitable for applications that needs high flexural and tensile strength, without compromising the concretes original compressive strength. Reduced workability, improved durability, reduced shrinkage and decreased deformation are among the results when adding starch to the mixture.

The temperature rise inhibitor and heat release controlling admixture also points to the possibility of starch being suitable as a retarding admixture for use in warm environments and can be used as a substitute for retarders and viscosity modifying admixtures.

Further investigations are necessary to determine the suitability of starch under different environmental conditions in order to understand the full impact of durability properties of the material in concrete.

### Gum tree lignin

Research investigating the use of GAK as an admixture result in:

- Improved sorptivity, increase initial and setting time
- Denser microstructure
- Improved compressive
- Improved durability

Use of GAK as admixture have advantages that it does not need further preparation before use. Concrete show higher durability and result more sustainable concrete. GAK is not easily accessible all over the world, but in certain areas, such as south Africa, it is cheaper and more accessible than other admixtures in the market, and it can improve waste management. This material may be of interest in some areas in the world, but not widely used.

### Egg – broiler hen

Research investigating the use of egg component as admixture result in:

- Accelerated hydration process and setting time at early stage
- Lower density
- Increase compressive strength
- Increased splitting tensile strength and modulus of elasticity
- Improved durability

We conclude by using lyophilised liquid egg components as NAD together with FA, all test gave that NAD improve the compressive strength and splitting tensile strength, at all ages. Modulus of elasticity align with the results of the compressive strength. 0.25 % is the recommended dosage of NAD, higher dosage delays the hydration process due to biofilm created by the NAD.

Since density are lower in FA and NAD concrete than pure cement mixtures, this influent the final load at the construction structure, it may be considered as a costs effective sustainable concrete. On the other side, the use of egg compound in an industrial scale, will compete with food production. This need to be considered not to compete of the same resources if it is not sustainable in the area, due to UN SDG 2, zero hunger.

### 4.2.4 Fillers

#### Egg shell powder

Research investigating the use of ESP as filler result in:

- Less dense microstructure, poorer bindings in ITZ
- Do not develop strength
- Do not need much treatment
- Radioactive shielding performance

It is positive that ESP do not need much treatment before use. To be considered as cement replacement has ESP in combination with microsilicia shown similar strength results as OPC and may be used if lower workability is acceptable. Adding plasticizer can be suggested. Flexural, compressive and tensile strength were reduced by increase of ESP dosage in the mortar, which can be explained by change of the microstructure where the eggshells have poorer bindings in the interface than ordinary cement. Since EPS do not develop the strength, it is more suitable as filler as replacement for sand in the concrete

ESP showed radiation absorption coefficient, and may be considered in concrete in radiation environments, as room with x-ray of cargo at airports and in examination rooms at hospitals.

Egg shell from poultry industry are a large contributor to food waste in many countries, and by use of ESP in larger scale the waste landfills can be locally reduced, and concrete be more sustainable due to less need of fine sand and fillers, which may be limited access in some areas.

### Rice husk Ash (RHA)

Research investigating the use of biochar from Rice husk as filler result in:

- Improve density
- Improve internal curing process
- Increased mechanical properties
- High pozzolanic behaviour

RHA improve strength and durability of the concrete, due to highly pozzolanic behaviour. Therefor it is interesting that RHA may be used as reactive filler. By use of organic materials, the concrete density is reduced and will influent the total weight of the final construction structure, which result a positive effect on loads onto ground or supporting structure, without compromising the mechanical properties. On the other side the benefits of lower costs on supporting structure, may be lost due to higher costs for preparing the rice husk ash compared to natural materials as sand and gravel.

RHA is of interest for further researches due to the high pozzolanic behaviour.

### Nanomaterials

Cellulose nanomaterials as fillers and reinforcement in concrete. These components can make the concrete more sustainable when we can higher the elastic modulus while maintaining the same water-to-powder ratio. This is a sustainable alternative compared to the conventional method such as increasing the cement content, use of silica fume and using stiffer aggregates

Studies based on cellulose (polysaccharide) in geopolymer concrete instead of OPC have shown the good results, interesting to study in future experiences. Samples with only small amount of cellulose, hemicellulose and lignin in GP matrix, showed slightly lower compressive strength than pure geopolymer concrete. This can be explained by less geopolymerization, since hemicellulose degrade the alkaline environment by generating carboxylic acids. By higher hemicellulose or lignin content, reduction in both flexural and compressive strength was observed.  due to more porous morphology and lower density, preheating the materials did not influent properties in the mortar positively, as seen in biochar. This may result that neither lignin nor hemicellulose are good alternatives in Bio-Geopolymer concrete. Cellulose have shown much better results, and Nano cellulose have shown improved freezing thawing resistance, which are positive abilities in the case of making more durable concrete.

There has been proposed some concern about inhalation of nanoparticles that need to be explored (Hisseine et al., 2019). In case of the nanocellulose new catalysts and/or recovery processes is brought up as a potential to reduce production costs and put nanocellulose into the concrete industry (Moon et al., 2011).

### 4.2.5 Summary

*Table 2 Summary of the most interesting properties found*

| | **Optimal dosage [wt%] cement** | **Obtained properties** |
|---|---|---|
| | | **Binders** |
| **CBA** | | Pozzolanic behaviour |
| **RHA** | | Pozzolanic behaviour |
| **Additives** | | |
| **Bio GP** | | Allows lower curing temperature in GPC<br>Better resistance against chemical attacks |
| | | **Admixtures** |
| **MWBC** | 1 | Improved hydration early stage, reduced heat<br>Lowest flowability of BC<br>Reduction in initial setting<br>Compressive strength increased by 15-20 %<br>MC heated 5-700degrees – high increase of compressive strength |
| **FWBC** | 1-2 | Late sorptivity increased by 2.2 times<br>Less porous than other BCs<br>Compressive strength increased by 10 %<br>Flexural strength depending at type of FW |
| **RWBC** | 5 | Improved hydration early stage<br>Compressive strength decreased by 7 % |
| **SCBA** | 10 | Increased setting time<br>Increased air permeability, without sorptivity changed<br>Compressive strength increased by 13 % in LWC<br>Pozzolanic behaviour<br>Significant increase in resistance against chloride attacks |
| **Sat. BC** | 15 | Setting time reduced<br>Improved mechanical strength in MWBC |
| **BC with active C** | 30 | Allows larger dosage of BC may be added in mortar, up to 30%<br>Improved thermal conductivity and sound absorption effect |
| **RH sp** | 0.5% of FA | Highly suitable superplasticizer for GPC |

| | | |
|---|---|---|
| **Starch** | | Increased setting time<br>Reduces shrinkage and decreased deformations<br>Improved compressive, split tensile and flexural strength |
| **GAK** | 0.8 | No modification methods needed<br>Improved sorptivity<br>Increase initial and final setting time |
| **Egg (NAD) + FA** | 0.25 | Accelerate hydration process<br>Lower density<br>Reduce workability<br>Improved bond strength<br>Reduced initial setting time at early stage<br>Increased compressive and splitting tensile strength<br>Increase modulus of elasticity but varied depending on aging<br>Lower costs than similar admixtures (34% less) |
| **Fillers** | | |
| **EPS** | | Do not develop mechanical strength<br>Increased radioactive shielding performance |
| **RHA (BC)** | | Improved internal curing process<br>Higher density<br>High pozzolanic behaviour |
| **Nano cellulose** | | Improved bond strength<br>Improved freezing-thawing resistance |

### Applications

The different materials discussed have a wide range of applications. Both Coal Bio ash and rice husk ash show promising abilities for cement replacement. Geopolymer concrete require special curing conditions, and it is suitable for prefabricated products, but by adding bio-additives the improved properties give it a wide range of applications.

Biochar can be used in applications that require high compressive strength and gives excellent sound absorption, insulation and building energy efficiency, which can be utilized for buildings that require special properties, such as low-energy houses. It also has potential for use as a carbon sequestering admixture.

Rice husk can be utilized as a plasticizer for GPC and GAK and egg as an admixture for improved durability. Egg can also be used as an admixture to reduce the final load of the construction.

Starch can be successfully utilized as an admixture in applications that requires high tensile and flexural strength and as a temperature rise inhibitor, to control heat release rate and as a retarding admixture for warm environments.

Egg shell powder, with good radiation absorption capacity can be used in radiation environments, such as x-ray rooms in hospital or airports.

Rice husk ash is a feasible alternative for high strength concretes and nanocellulose gives good freeze-thaw resistance for use in environments with shifting temperatures.

### Environment and sustainability

The main goal for UN sustainable development goal number 13 is to reduce the environmental impact from industry and production of products. When it comes to the construction business and concrete production, it is natural to study the different materials closely and see if there is any option to gain some environmental advantages without losing the requested properties. To replace or reduce the use of cement by addition of local available biomaterials such as coal bio ash or rice husk ash, is one way of producing more sustainable and cost-effective concrete.

Some of the materials discussed are already available as by-products from other industries, which makes utilizing them a waste management measure in addition to the reduced emissions related to replacing the material originally used. By utilizing locally available materials we also contribute to local industry and a more sustainable economy in rural areas. One important issue to be aware of is that some of the materials discussed, such as egg materials, are already used as food products, and competing for these recourses should be avoided, especially in areas dependent on this production.

Materials that provide better durability for the concrete contribute to longer lasting structures and less use of materials, which makes for a more sustainable industry.

The fact that bio-additives can lower the curing temperature of GPC and reduce the emissions related to GPC production.

Using biochar is, in addition of being a waste reducing measure, a good way to reduce the amount of cement used and lower the $CO_2$ emissions related to concrete industry. The good insulation properties also lead to better energy efficiency in buildings, which is also a good environmental impact.

ESP can, by replacing fine sand in concrete, contribute to avoid depleting natural recourses, and reduce the emissions from mineral aggregate and filler production. It is also a good alternative for concrete production in areas that does not have access to fine sand locally. The fact that it might not require treatment before use makes it very environmentally friendly.

Nanocellulose makes the concrete more sustainable by being able to increase the properties without increasing cement content or using silica fume. However, nanoparticles may be a health hazard for workers in the industry.

### Further research

The research all over the world for environmental protection of natural resources and the eco-system have led to innovation of new materials using by-products from different industries in concrete. According to our study, these areas need more research:

- The impact of bio additives on reduction of required external heat and other properties in GPC, for a more sustainable material. As well as the use of nanocellulose instead of OPC, and the potential health hazards related to inhaling nanoparticles.
- Exploring the application of biochar both as admixture and as fillers in mortar. As well as the use of biochar as a carbon sequestering admixture for carbon capturing and storage.
- The durability of starch admixture under different environmental conditions

In recent years, countless studies have been carried out to identify pozzolanic materials in concrete and mortar worldwide to achieve better mechanical properties and provide sustainable concrete. Materials of pozzolanic behaviour are of interest for further research. In the research the materials of interest are coal bio ash, RHA and SCBA. RHA shows many interesting properties, that need to be further studied as both a binder and reactive filler.

# 4.3 Aggregates

## 4.3.1 Bio-aggregates in LWAC

### Wood

Addition of sawdust result in:

- Increased workability
- Significant reduction of early shrinkage
- Decreased modulus of elasticity
- Increase in the values of rupture strain
- Improved first crack and total fracture toughness
- Increased water absorption, but within the maximal allowable water absorption for construction materials.
- Considerably decreased thermal conductivity

Saw dust is as a replacement for sand. It is both cheap and available everywhere in large quantities. Utilizing it would also serve as eco-friendly disposal of wood waste, and not contributing to the issue of emptying natural sand reservoirs, hence it is an eco-friendly alternative to sand aggregates. The compressive strength declines slightly with small replacements, but more rapidly at bigger replacements *(Figure 34*). Although, the fact that the compressive strength proved to be within the required limits of concrete grade M30, and the number of other positive properties, like early shrinkage reduction and fracture toughness, makes it suitable for a large number of structural applications. The decrease in thermal conductivity and good results from energy efficiency tests makes it especially suitable for reducing energy use and emissions in buildings. It is also free from harmful chemicals, and can be used without treatment, making it safe to work with. All in all, this is an excellent alternative to sand aggregate.

The good results from replacing coarse aggregate with wood gives another possible application for wood waste, with the same benefits as the sawdust.

Given appropriate mix design and correct level of replacement, wood waste can be used as aggregate for structural concrete that meets code requirements.

#### Sunflower and corn

Addition of sunflower and corn result in:

- Decreased workability
- Increased water absorption
- Decreased strength

Even though the incorporation of sunflower seed husk leads to decreased strengths *(Figure 35 and Figure 36)* many of the test specimens have proven to classify as structural lightweight concrete when considering weight and compressive strength, and as structural and isolation concrete meeting both strength, resistance and insulation requirements. This makes it a good and sustainable replacement to mineral aggregates, which might reduce the energy need and pollution associated with production of the aggregates and contribute to saving the natural recourses.

Treating corn and sunflower aggregates before use can alter the mechanical abilities of the concrete to the better and gives many possible applications. Again, the value of the replacement must be weighed against the negatives of the treatment. Changing the binder also has an impact and might be a more environmentally friendly way of making use of the good abilities of these aggregates.

These researchers also point out that there is a lack of standard procedures or common approaches in this area, with varying testing conditions, which leads to arbitrary decisions and a large diversity of results in the performance of bio-based materials.

#### Fruit shell in LWAC

LWAC of carbonized peach shell (CPS) and carbonized apricot shell (CAS) leads to:

- Reduced water absorption to less than 10 %
- Increased bonding capacity of the ITZ
- Significantly decrease creep stain

- CPS showed largest increase of mechanical properties compared with PS
- CAS showed highest mechanical properties in MPa
- Decreased modulus of elasticity
- Increase in Modulus of Elasticity

Significant increase in mechanical properties were shown in test comparing raw aggregate (PS and AS) and carbonized fruit shells. Shown in *Figure 37* and *Figure 38* CPS increase the most compared to PS, but it is important to note that CAS shows the highest values of mechanical properties, and considered as suitable for production of high-strength LWAC. The water absorption was reduced by use of carbonized shells, due to the increased bond in the mortar.

By use of fruit shells reduction of agriculture waste can be reduced, and carbonation of the shells are considered as an inexpensive technology, but method need high amount of energy during heating.

**Other aggregates**

Hemp has for a long time been considered the reference agricultural resource for vegetal concrete, but it has never been amongst the most widely available bio-products. Therefore, it has become necessary to consider other possible sources of bio-aggregate available locally in greater quantities.

### 4.3.2 Recycled aggregates

Conventional concrete consists of about 70-80 % aggregate by weight, and crushed rock, gravel and sand are most common used aggregates. The environmental impact of exploitation of raw materials need to be reduced. Therefor a variety of materials are tested as a substitute for above mentioned aggregate, to produce more sustainable concrete. The use of demolition waste from construction structures is important contribute for reduction of the $CO_2$ emission from concrete industry. This will also contribute to less resource shortage. Recycling concrete as aggregate is not within the scope of our thesis, however, some biomaterials in combination with RA are explored.

Recycled materials as aggregates has often higher water absorption and week bonding in the matrix and do need to be threated to be a valid alternative to natural aggregates. Several methods have been developed to reduce the water absorption.

The good strength properties of the recycled MDF aggregate are promising, but it requires treatment to be taken into consideration when evaluating the environmental gain of using the material. Being sensitive to humid environments clearly limits its applications, as it can be used only in dry environments.

Observations of bacteria and Nano silica in combination for reduce water absorption of RA, show a strong trend to obtain suitable properties for low and medium strength concrete. This modification method is more environmentally safe and energy efficient solution, compared with chemical treatment methods. To increase durability in RA, it will be more suitable for concrete production. This will reduce demolition waste and the environmental impact from waste material and reduce tearing on natural resources and landfill disposal.

### 4.3.3 Summary

#### Applications

Wood waste can be used as a replacement for both sand and coarse aggregate in structural concrete for a large number of applications, as it meets code requirements. It is especially suitable for low-energy buildings and passive houses, due to excellent results from energy efficiency tests.

Sunflower and corn aggregate concrete have potential to classify as structural lightweight concrete and insulation concrete and is thus a good option for many applications. Fruit shell show many of the same abilities and with good strength properties it is suitable for high strength LWAC.

Recycled aggregates, when treated properly, can be used in low to medium strength concrete.

#### Environment and sustainability

In regard to the $CO_2$ balance, the RA and organic material play a large role in reducing the density of concrete and reduce weight of the final construction structure. While environmental benefits are large by using recycle aggregate, the use of biomaterials may be more expensive than use of sand and gravel.

The aggregates discussed are all available and cheap and using them contributes to more reuse, recycling, better waste disposal, reduced pollution associated with mineral aggregate production as well as not emptying natural sand reservoirs.

The sawdust's good energy efficiency properties will help reduce the emissions related to the finished structures. Hence, it has an environmentally friendly impact through many steps of its life cycle. Being safe for the workers is also a gain.

The good strength properties of the recycled MDF aggregate are promising, but it requires treatment to be taken into consideration when evaluating the environmental gain of using the material.

Using bacteria to improve the properties of RA will contribute to waste reduction and reduced tearing on natural recourses.

### Further research

According to our study, these areas need more research:

- Long term durability of bio-aggregates in concrete under different environmental exposures
- Further studies of RA are necessary to investigate on long term performance. It has also shown that other wastes from industrial activities may be interesting to study as aggregates to achieve sustainable concrete.
- Core shell aggregate based on use of cold bonding method, where the energy consumption is much lower than carbonization, showed promising result of physical and mechanical properties. This shows that cold bonding technique should be further studied, and the core-shell aggregate may be developed for production in the future.
- Developing standards for common approaches and procedures for testing bio-based products

## 4.4 Self-healing in concrete

Self-healing in concrete helps extend construction lifetime and reduce maintenance work by enclosing the cracks as soon as possible to prevent further deterioration. When the cracks are sealed, chloride ingress through the crack are prevented and the reinforcement is protected from corrosion. The crack sealing capacity is clearly limited as showed trough the review. The highest crack-sealing reviewed was 1.24 mm. It is shown that the natural self-healing that occur in concrete under the optimum healing condition is crack sealing about 0.64 mm with conventional blends and that blends with fly ash can achieve a little higher crack sealing with a mean value at 0.84 mm (Rajczakowska et al., 2019). These results are obtained in laboratories under controlled and facilitated conditions and it is reasonable to believe that this is a higher level of what can be expected in the natural environment of concrete constructions.

The common level referring to autogenously self-healing in concrete is crack-sealing 0.30 mm. Cracks under this level can close in exposure of water because of secondary hydration and precipitation of calcium carbonate ($CaCO_3$). The process is dependent on the availability of carbon dioxide. The exposure condition like temperature and water is also of great importance. The studies regarding concrete added with crystalline admixture can support the claim that refine curing condition can achieve a higher level of crack sealing. It was pointed out that the exposure condition and the initial crack width were the most important factors for crack sealing in this study. The presence of water was important to both conventional concrete and the concrete with crystalline admixture. Both fly ash and crystalline admixtures, the content in the sample with the highest crack sealing in that study, are available in commercial concrete blends and the develop that has been done considering these materials is therefore positive also seen from the self-healing perspective in addition to the substituting of clinker.

### Superabsorbent polymer (SAP)

It is seen that cracks can heal when exposed to water. Superabsorbent polymers (SAP) secure longer access to water because of its absorption ability and can therefore contribute to accelerate crack sealing in the autogenous healing. The issue concerning SAP`s is the impact the incorporation has on the concrete`s mechanical properties. To ensure workability more water is usually added to the mixture. This may affect the strength due to a higher w/c-ratio.

The void that is made from the SAP has also an impact. Hindering loss in mechanical strength is crucial on load bearing structures. Some results concerning loss in compressive strength is collected in the figure underneath. A trend that can be seen through the investigation is generally that increasing SAP amount leads to loss in compressive strength. The particle size of the SAP`s also has an impact. In the review we have an range in addition of SAP from 0.1 m% to 13 m%. The additions give a loss in compressive strength measured from a reference concrete with the same w/c-ratio that range between 2 % and 87%. It can generally be seen that increasing content of SAP`s leads to loss inn compressive strength.

Adding calcium nitrate is mentioned as a possible solution to depresses the initial swelling of SAP which allows a higher SAP content without affecting the strength to such an extent and seem therefore like a method that can allow increased dosage to develop a healing system based on SAP`s that also ensures the workability of the concrete. Lee et al. detected models in their study that suggest that cracks larger than 0,4 mm can be self-sealed with SAP by increased dosage. It is therefore seen a possibility to improve the autogenous self-healing with the content of SAP`s.

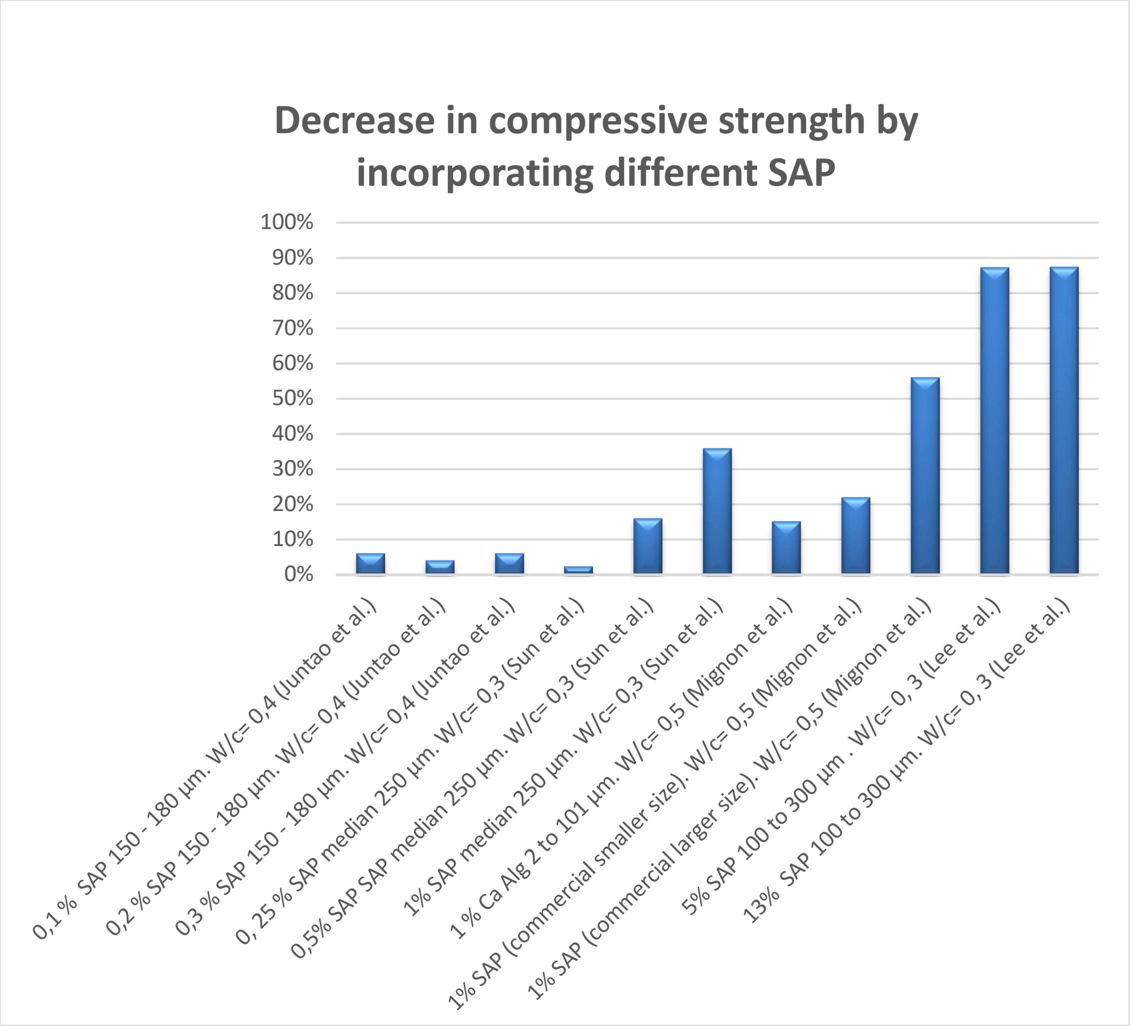


*Figure 44 Decrease in compressive strength with different sized and amount of SAP and different w/c-ratios (Juntao et al., 2017, Sun et al., 2019, Mignon et al., 2017, Lee et al., 2016)*

A way to improve self-healing without compromising mechanical strength is to use SAP with a high absorption ability. The commercially available SAP that has been rendered earlier in this paper appears as less satisfactory at this point. A key point for practical application of SAP seem to be specially designed SAP`s that are small enough to prevent the undesirable effect on strength and provide enough water supply to enable effective self-healing, as shown by the biological alginate beans. This seem also as a solution to develop a more cost efficiency SAP since the low-cost biopolymers can absorb a high amount of water that gives a higher utility for the amount used (Mignon et al., 2017). It is reasonable to believe that the effect by adding calcium nitrate also could be relevant to the biological alginate SAPs regarding the impact on compressive strength and possible impact on the workability.

The alginate beans (CaAlg) shows promising results with only a loss in compressive strength at 15 % with an addition at 1 m%. Further on, the alginate beans had an impressive moisture uptake ability with an uptake at 169 % its own weight at 90 % RH. The commercially available SAP`s had in comparison an uptake at 83 % and 84 % its own weight at the same RH. Alginate beans therefore appears as a sustainable approach with self-healing by SAP since they are fabricated by bio-based materials, shows a relative low impact on compressive strength and in addition can serve as large moisture reservoirs that is essential to accelerate the self-healing in concrete. The technique is a cost-effective solution which enable it to a future commercialize.

### Microbially induced calcium carbonate precipitation (MICP)

As earlier reported, an increased dosage of substitutes in concrete often leads to an unwanted loss in mechanical strength due to the increased pore volume. This is also experienced with increased size of microcapsules rendered in the study by Du et al. The smallest microcapsules with an average size at 90 μm had a significant increase in compressive strength at 28.2 % compared to the control specimen without capsules. The largest capsules with an average size at 480 μm had at decrease at 6.2 %. This shows that it is possible to develop an encapsulation system without compromising the concrete`s advantage regarding strength and furthermore the durability of the construction. The size of the capsule must be adapted to the healing agent. Bacterial spores are typically smaller than fungal spores, however, the size of the spores are further dependent on the species. Du et al. used a chemical healing agent and neither the shell material nor the preparation method is likely to be directly transferable to a sustainable encapsulation system for live microorganisms. Nevertheless, it is shown that small sized capsules with hard shell is a possible method for an encapsulation system that don`t compromise the compressive strength in concrete.

The technique concerning encapsulation appears as detailed and complex and it can therefore be favourable to develop a technique that is more facilitated and easier to produce in large scales to lower costs. A system that can both serve as the aggregate and a healing agent seem practical and an opportunity to avoid multiple additions of chemicals or other materials that are not environmentally friendly. A carrier compound with the right size, surface and mechanical strength that can substitute some of the aggregate seems like a cost-efficient approach and a possibility to preserve the mechanical strength in concrete. At the same time the compound needs to protect the microorganism and ensure efficient calcium carbonate precipitation and the workability need to be ensured in some degree. Several carrier compounds have been tested as; light weight aggregate, recycled coarse aggregate, Nano platelets, hydrogels, polyurethane, diatomaceous earth and cellulose fibres.

Carrier compounds of diatomaceous earth has shown pozzolanic effect that must be considered as a positive side effect in a self-healing system since such properties could contribute to stronger concrete or even enable use of less cement in the mixture. This should be interesting for future investigations.

Porous carrier compounds like light weight aggregate that has shown a decrease in compressive strength can be suitable self-healing systems for light weight constructions (Tziviloglou et al., 2016). Considering this, it is a possibility that porous carriers could be applied in light weight constructions and carriers that have shown better results concerning mechanical strength, like diatomaceous earth, could be suitable for heavier constructions. Based on the review it is seen a future potential to optimize the healing system for the relevant application.

To ensure the liveability of the bacterial self-healing agent it is shown that a carrier compound is needed. The direct bacteria incorporation had the lowest crack sealing at 0.37 mm which is at the same level as the autogenous crack sealing. The calcium precipitation of microorganisms is more efficient than the chemical precipitation contributing in autogenous self-healing. The precipitation efficacy is also depending on the bacteria specie and the biological pathway for the precipitation. The result with the highest crack sealing is 1.24 mm achieved by using the sugar-coated expanded perlite with potassium magnesium phosphate cement shell and Bacillus cohnii as a healing agent after 28 days of healing. The highest crack sealing result from the review is collected in the table below, sorted from the highest to lowest level.

*Table 3 Comparison of crack sealing in different carrier compound, bacteria types and w/c-ratio sorted from high to low crack sealing*

| Crack sealing | Carrier compound | Bacteria type | W/c-ratio | Reference |
|---|---|---|---|---|
| **1.24 mm** | Sugar-coated expanded perlite with potassium magnesium phosphate cement shell | Bacillus cohnii | 0.6 | (Jiang et al., 2020) |
| **1.22 mm** | Expanded perlite | Anoxic bacteria culture | 0.4 | (Zhang et al., 2019) |
| **1.10 mm** | Recycled coarse aggregate | Bacillus substilis | 0.4 | (Khushnood et al., 2020) |
| **0.81 mm** | Graphite Nano platelets | Bacillus substilis | 0.4 | (Khaliq and Ehsan, 2016) |
| **0.79 mm** | Sugar-coated expanded perlite with acidic sulfoaluminate cement shell | Bacillus cohnii | 0.6 | (Jiang et al., 2020) |
| **0.79 mm** | Expanded perlite | Bacillus cohnii | 0.4 | (Zhang et al., 2019) |
| **0.73 mm** | Expanded perlite | Bacillus cohnii | 0.4 | (Zhang et al., 2019) |
| **0.61 mm** | Light weight aggregates | Bacillus substilis | 0.4 | (Khaliq and Ehsan, 2016) |

It is of prime importance that the bacteria can survive the harsh environment that concrete offers. The review has also shown that bacteria cultures have different precipitation efficiency and that spore concentration also is a key point. It is showed that a minimal number of bacterial spores are required to ensure the healing process. Some studies explicate different suitable spore concentration to different bacteria cultures to achieve a high level of calcium precipitation (Zhang et al., 2017, Wiktor and Jonkers, 2011). This leads to an assumption that the optimized spore concentration may be related to the relevant bacteria species. Another point revealed is also the form of calcium carbonate (calcite, vaterite or aragonite) that is precipitated plays a role and that other nutrients beside yeast extract leads to a more rapid and efficient calcium carbonate precipitation.

Earlier in this paper it has been reviewed that Khaliq and Ehsan and Khushnood et al. investigated bacterial self-healing with different carrier compounds. The findings from these two studies are collected and presented in the table below. As we can see the crack sealing capacity is reduced by about 50 % for several of the samples at pre-cracking in older specimen. The reduction is associated to crushing of bacterial spores immobilized directly due to the reduction in the pore size caused by hydrated cement (Zhang et al., 2017, Wiktor and Jonkers, 2011). This raise an issue how to ensure a long-lasting effect of self-healing with bacteria and that the carrier compound can be of great importance to ensure this. Therefore, one must consider both the impact on compressive strength, crack-healing capacity and the long-lasting effect to develop a convenient carrier compound.

*Table 4 Comparison of crack sealing with different carrier compounds*

| Carrier compound | Crack sealing in 28 days in specimens pre-cracked at 3 days | Crack sealing in 28 days in specimens pre-cracked at 28 days | Reference |
|---|---|---|---|
| **Light weight aggregates (LWA)** | 0.61 mm | 0.52 mm | (Khaliq and Ehsan, 2016) |
| **Graphite Nano platelets (GNP)** | 0.81 mm | 0.38 mm | (Khaliq and Ehsan, 2016) |
| **Direct bacteria incorporation** | 0.37 mm | 0.15 mm | (Khaliq and Ehsan, 2016) |
| **Recycled coarse aggregate** | 1.10 mm | 0.6 mm | (Khushnood et al., 2020) |

Even if there was an experienced reduction in the healing in later age pre-cracking the recycled coarse aggregate with Bacillus subtilis as a healing agent emerges as a promising healing system with a crack sealing at 1.10 mm. Still, the solution presents an increase at 119.4 % in cost compared with conventional concrete with the same 28 days compressive strength (Khusnood, 2020). This issue demands future efficiency improvements to present a relevant solution for a sustainable alternative. Zhang et al. presents microbiological consortia instead of using pure bacteria cultures as a possible solution to a cost-efficient system with a 61 % decrease in production costs. Developing of cost-efficient strain and cultivation system that can serve the self-healing purpose seems like crucial for future realization. Further on it is also shown that it is possible to develop a full-out bio-based self-healing system with cellulose fibres and bacteria. This solution presents a low-cost possibility but also present the same issues concerning compressive strength and survivability as shown for the other systems. In addition, it can provide autogenous healing due to the good water absorption ability.

The initial crack width plays a significant role to the crack sealing capacity. Narrower cracks are easier to heal than larger one and it is known that the presence of dispersed fibre reinforcement can control and limit crack width. Fibre can therefore achieve effective self-healing in the whole construction throughout lifespan, starting from the early ages. Self-healing by fibres have not been an independent part of this investigation but could be interesting for future investigations. Natural fibres like basalt can used as an addition to prevent strength and prevent large cracks combined as a healing carrier. Bio-based materials like flax, sisal, coconut or jute fibres has shown promising results concerning compression strength in the review of fibre reinforcement and may serve as suitable future carriers. In this case a secondary advantage of moisture absorption may occur and, in this way, also contribute to a simultaneous autogenous self-healing. Solutions like this could present a holistic and sustainable self-healing system with possible better impact on compressive strength than showed in the study regarding cellulose fibres.

Self-healing systems with bacteria has a weakness concerning long-term self-healing efficacy. Limited biomineralized $CaCO_3$ production by bacteria after introduction into the incompatible concrete matrix is a major challenge of this technology. It has been reported no loss in viability for over six months when the bacteria spores were incorporated. It has also been reported live cells at 330 days. Out of this we can assume that it is possible to develop a long-term system with the right combination of bacteria and protecting systems. Techniques to ensure growth and reported viability of spores is therefore essential for a long-term self-healing system based on bacteria.

An alternative microorganism for self-healing system mentioned earlier, is fungi. Fungi have been reported growing and existing as an important component on for example limestone, sandstone, granite and marble. Fungi are also effective concerning calcium carbonate precipitation and can promote large amount within short time. Fungi can promote mineral precipitation trough both biomineralization and organomineralization unlike bacteria that can promote precipitation only by biomineralization. Considering this, fungi appears as a possible preferred candidate in a self-healing system in concrete. Furthermore, Jin et al. reports that there is a possibility that the incorporating of fungal spores may have less negative impact on the compressive strength in concrete. In the light of this it seems like it is a lack of investigations on this possibility as a self-healing system. Searches in the EI Compendex database with the combination *"fung*biomineralization concrete"* obtain 10 matches compared to the combination *"bact*biomineralization concrete"* with 91 matches. The studies found was focusing on appropriate species of fungi for possible application as a self-healing agent, investigated on fungi strains which can survive the environment of concrete and at the same time be an efficient calcium carbonate precipitator. This must be considered as the first step in a fungal self-healing system.

The same issues concerning carrier compounds is likely to be present for fungi as it is for bacteria and a suitable carrier compound must be used. A possible advantage for fungi is that it could present a more cost-efficient self-healing system because they are easier to produce in large quantities and since the nutritional needs are simpler (Jin et al., 2018). Based on this a fungal self-healing system seems to be a topic for future investigations for sustainable self-healing system.  Furthermore, Menon et. al presented in their study another interesting possibility for this technique as a maintenance action for existing concrete infrastructures by suggesting injection of fungal spores and their nutrients into cracks for self-healing (Menon et al., 2019). If this method can be offered comprehensive as a cost effective, easily operated and reliably system it can promote sustainability. A possible challenge to a method like this is that it could possible enable unwanted growth from other unwanted microbes. Surface treatment that could prevent extensive maintenance work like suggested by this method has not been a part of this investigation and further comparisons will not be done but it is worth mentioning as an interesting case for future investigations.

The main issue of crack healing systems due to the calcium carbonate precipitation performed by microorganism is if it can ensure strong and durable concrete for a long time that can ascribe the cost and other efforts. Further on, to what extent can we compromise some mechanical strength in the purpose of preventing and delaying further deterioration. These issues seem difficult to make further assessments of without life cycle assessments and long-term studies in the natural environment of concrete. In situ and upscaled investigations would give valuable information about the cooperation between autogenous and autonomous self-healing, the efficiency and the longevity in a bacterial self-healing system. Based on the conducted review the system seems immature for these kind of investigations at time.

Another potential for improved self-healing efficacy that has not been explored trough this thesis is nanotechnology. The potential for nanotechnology to open new opportunities in composite design is present. Nanotechnology may contribute to solve issues like oxygen and calcium limitation and lack of C-S-H formation by Nano-additions.

## Summary

Bacterial self-healing system appears as effective at sealing larger cracks by calcium precipitation and it is a great potential to explore the effectiveness of fungi. In this review the maximum crack sealing was 1.24 mm. Furthermore, the review has revealed that the type of bacteria that is used and the concentration of the healing agent is of importance considering mechanical strength beside the carrier compound that is of prime importance. Several of the encapsulation and carrier compound that was used to protect the healing agent showed unwanted impact on the concrete`s mechanical properties. Microbiological self-healing system with a carrier compound with mechanical properties that are similar to natural aggregates seems like a sustainable method for future use.

Self-healing systems with bacteria has a weakness concerning long-term self-healing efficacy. In addition, the technique is complex and costly. Conventional blends with fly ash have achieved crack sealing with mean value at 0.84 mm by water exposition. This is about the mean value of crack-sealing achieved with microbially calcium carbonate precipitation that is reviewed. Further effort and investigations should focus on a cost-efficient bacterial strain and a protecting system that don't affect the compression strength like achieved by sugar-coated expanded perlite with potassium magnesium phosphate cement shell or recycled coarse aggregate with a cost-efficient bacteria culture or fungal strain. Further on, it seems like a potential to refine the autogenous self-healing potential by using biological SAP`s and crystalline admixture and achieve a relatively high autogenous crack-sealing. Fly ash seem to have a positive impact on crack sealing.

The initial crack width plays a significant role to the crack sealing capacity and the exposure conditions can have a great impact, specially water exposure. Fibre can contribute to achieve effective self-healing. Generally, it is a lack of full-scale tests regarding to both extended time aspect and tests in natural environment at this theme. Test like this could be valuable considering the impact of exposure condition and a possible cooperation between autogenous and autonomous self-healing and the long-term efficiency. Nevertheless, it seems like it is need for more research before this is applicable for a self-healing system based on microorganisms.

### Main challenges with self-healing concrete

- High cost compared to conventional concrete
- Long-term efficiency due to the survivability of the microorganism
- Decrease in mechanical strength in concrete when incorporating SAP`s, capsules or other protecting carriers

### Main gains with self-healing concrete

- Repairing cracks immediately without any external system
- Increased resistance to deterioration as corrosion and other attacks
- Higher duration and saved maintains cost
- Extended service-life that save use of new materials and costs

### Applications

Self-healing concrete is probably most appropriate for constructions that to a greater extent is exposed for deterioration, construction that is vulnerable in the context of future maintain work due to safety, cost and traffic management and therefore can defend the extra investment cost. Porous carriers could be applied in light weight constructions.

### Environment and sustainability

Self-healing concrete systems that ensure durable constructions by crack closure can reduce maintenance and extend the service life of constructions. Expanded service life decreases the need for replacing materials frequently. In this way durability offers sustainable advantages by saving use of raw materials, reduce emission and cost due to new production and avoid costly maintenance work. The durability in concrete is affected by the quality of the concrete mixture. The review has shown that addition of alternative materials can impair the quality of the mechanical strength in concrete and it is therefore also relevant to consider in what extend we can tolerate quality decrease with alternative methods that has a durability purpose and that leads to higher productions cost. In the case of sustainability, the carrier compound of cellulose fibres with bacteria as healing agents offers an extra dimension as a full-out bio-based self-healing system. The longevity of a structure or the application with a system like this must be further explored to decide the degree of sustainability.

The other issue is in what extend of sustainability the production of the healing agent and carrier compound or SAP offers. As an example, SAP`s made of biopolymer of alginate beads contains natural materials but depends on an extraction procedure and chemicals that is difficult to make sustainability assessment of. This is also the case in bacteria culturing and different encapsulations systems.

Carrier compounds made of expanded perlite (EP), light weight aggregate (LWA) and graphite Nano platelets (GNP) is made of natural resources like slate, clay and volcanic and metamorphic rocks and present a future risk of emptying natural resources. Considering this, reuse of materials like recycled coarse aggregate seems like a holistic sustainable approach to a self-healing system based on bio-based healing agents. The issue associated with weaker contact zone between cement paste and the aggregate (ITZ) formed between old and fresh concrete must be solved to maintain mechanical strength and durability. Milling techniques and different dispersion size and shapes of the carrier compounds can be considered as a possible managing improvement. For future practical implementation and sustainable assessments culturing microorganism and further refinement emerge as a technique that will be offered by niche industries while recycled coarse aggregate could be a locally available resource. The investigations concerning self-healing concrete is experienced as widespread with various methods, strains, carrier compounds and in what extend tests of strength and workability have been a part of the investigation.

### Further research

The self-healing theme is complex with various possibilities and issues and there is definitely need for a lot more research on this subject. The greatest challenges due to a self-healing system is the uncertainty associated with the long-term efficiency of the system, the impact the system have on the concrete`s mechanical strength and the high production costs. Further investigations should focus on documenting long-term viability of microorganisms and efficiency at pre-cracking since concrete constructions generally has a long lifespan:

- Investigations that explore fungal carbon precipitation in a self-healing system containing of a carrier compound with mechanical properties that are similar to natural aggregates and comparison with a bacterial self-healing system

- Investigations on cost-efficient bacterial culture and a carrier compound with mechanical properties that are similar to natural aggregates but still offers protection to the microorganism
- Cooperation between an autogenous and autonomous self-healing system and how different exposure condition can affect the healing capacity
- Microbiological self-healing surface treatments
- The results considering SAP`s with biopolymer of alginate beads seems promising considering both sustainability, compressive strength and absorption capacity and should be further explored. A research of alginate beans as a possible hydrogel carrier compound for microbiological self-healing systems could be interesting for future research but also autogenous crack-sealing with alginate beans alone is interesting
- Pozzolanic effect by using carrier compounds of diatomaceous earth
- Full-out bio-based self-healing and possible applications
- Natural fibres like basalt used as an addition to prevent strength and prevent large cracks combined as a healing carrier

## 4.5 Environment and the UN sustainable development goals

The discussed solutions contribute to meet the UN sustainable development goals (UnitedNations, 2015) we initially wanted to meet in the following ways:

**Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation:** Reducing use of limited recourses is met by finding alternative materials that are more abundant and renewable, such as alternative aggregates. Reduction of emissions and energy use associated with production and transport is met by suggesting materials that require less energy to produce, and among other things, choosing locally sourced natural fibres to limit transport. Also, the UN sustainable development goals state that small and medium sized businesses working with industrial processing and manufacturing account for about 50-60 % of employment, making local production of raw materials an important contribution to the economy in small societies and utilizing more of these raw materials we contribute to increased employment in rural areas. The least developed countries have a large potential for this kind of industrialisation.

**Goal 12: Ensure sustainable consumption and production patterns:** Resource and energy efficiency can be improved by increasing the properties of the concrete for less material needed, such as improved strength for reduced slab thickness, and by a higher rate of waste reduction, recycling and reuse of materials. Suggesting waste materials to be used in concrete production meets this goal in waste reduction and replacing non-biodegradable materials with biodegradables, such as steel and plastic replaced by natural fibres, contributes to increased possibilities for recycling and reuse. Issues on air, soil and water pollution from industry can also be party solved by replacement materials that are natural and require less harmful chemicals.

**Goal 13: Take urgent action to combat climate change and its impacts:** To contribute to the combat of climate change, the concrete industry must act now. This requires a lot of research on alternative methods and materials. Self-healing constructions increases the lifespan of the constructions and lead to decreased use of clinker and other non-renewable sources. By recommending areas to focus this research and possible solutions, we aim to contribute to meet this goal.

Some of the solutions reviewed also meet additional goals:

**Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture:** Being the single largest employer in the world, agriculture provide livelihoods for 40% of the world's population and is the biggest source of income for poor rural households. Expanding the production to also delivering products for use in concrete, such as waste materials from food production that can be used as fibre reinforcement, will give a higher employment and income rate to the relevant areas. It will also make the industry more resilient, as there are more legs to stand on.

**Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss:** Many of the materials reviewed are waste materials already available, and can replace natural materials such as for example stone aggregate. These can consequently help reduce the use of non-renewable resources and thus halt land degradation and protect ecosystems.

It is clear that the use of biomaterials has a positive environmental impact. However, the properties are not always improved, and the effect on the concretes properties is a key focus to make the solutions interesting for the industry. If not used the solutions have no effect.

# 5 Conclusion

Based on our research question «How can we use bio-based materials to get more sustainable concrete?", with the key aspects being how the materials reduce the environmental impact of the concrete, how they affect the mechanical abilities and durability, what possible applications there are as well as ethical and economic impacts, we have found the following answers.

**Natural fibre reinforcement**

- NFRC give workability issues, modelling difficulties and varying durability, but some of these issues seem to be fixable with the correct mix design or treatment before use. The main gains are increased strength and low weight. Some fibres show strength abilities sufficient to replace steel. Both bamboo, jute, coconut, flax and sisal are promising fibres emerging. Utilizing fibres contribute to good waste management, saving natural resources, and reduced emissions linked to producing traditional reinforcement.
- NFRC has a range of possible applications that should be carefully chosen with the different fibres' properties and limitations in mind. Among the applications are roller compacted roads and foundations, on ground slabs, floors for houses, retrofitting cylinders, passive houses, TRM systems and temporary reinforcement.
- Areas in need of further research are fibre treatment, admixtures and additives to solve workability and durability issues and long-term durability testing. This needs to be explored before we can safely utilize the fibres as reinforcement.

**Additives, admixtures, binders and fillers**

- Bio-additives in GPC improves durability and strength, can significantly reduce emissions and has a wide range of applications., and is thus a very promising material for sustainable concrete. Further research should be done on how this affects other properties.
- Biochar is a promising material suitable for applications that require compressive strength or good insulation properties and energy efficiency in buildings. It contributes

to reducing amount of cement necessary and the area of biochar as a carbon sequestering admixture is especially interesting for further research.

- Materials with pozzolanic behaviour are especially interesting for further research. Rice husk Ash and coal bio ash are materials with wide ranges of applications and show promising abilities to replace cement for more sustainable and cost-effective concrete.
- There is a variety of biomaterials that can be utilized as admixtures, additives and fillers, all with their own set of abilities that can contribute to more sustainable concrete with better properties.

**Aggregates**

- Both wood waste, sunflower, corn and fruit shell can be utilized as aggregates, and has potential to meet code requirements for several different types of concrete. In a sustainability view this contributes to waste reduction and limits pollution from aggregate production. Long term durability must be studied.
- Core shell aggregate based on use of cold bonding method showed promising result of physical and mechanical properties. This shows that cold bonding technique should be further studied, and the core-shell aggregate may be developed for production in the future.

**Self-healing**

- Self-healing concrete systems can reduce maintenance and extend the service life of constructions. Expanded service life decreases the need for replacing materials frequently. In this way durability offers sustainable advantages by saving use of raw materials, reduce emission and cost due to new production and avoid costly maintenance work
- Sustainable self-healing system based on microorganisms must show greater advantage in future investigations that is worth the effort both practical and economical. This could be advantages that can prove a long-lasting and efficient crack-sealing effect higher than a further developed autogenous self-healing system that has shown a similarly healing effect. Microbially induced calcium carbonate precipitation (MICP) by fungi should be investigated

- Full-out bio-based self-healing with natural fibres and microorganism is possible, but present issues like long-term efficacy and impact on mechanical strength. It can possible provide autogenous healing due the high absorption abilities of natural fibres
- Autogenous self-healing systems based on SAP`s of biopolymer containing alginate beads seem promising and should be further investigated

**General**

- There is a lack of common approaches and standard testing conditions that makes it hard to make good comparisons between materials and that lead to a large range of variables and results. With this available, we could answer questions about the effect of mix designs, w/c-ratio, treatment and curing conditions have on the strength and durability of the concrete.

"*How can we use bio-based materials to get more sustainable concrete*?".

In conclusion there are bio-based materials available that can be used due to their pozzolanic behaviour without impairing the quality of the concrete. For enhancement of concrete, some bio-based materials can be added for increased durability in chemical environments, for crack-sealing or as fibre reinforcement. Overall these bio-based materials are more environmental than both cement and ordinary concrete additives used today, and therefor show great potential for making more sustainable concrete. The majority of the materials also present challenges, which must be further researched.

# 6 References

ACI, A. C. I. 2010. ACI 212.3R-10: Report on Chemical Admixtures for Concrete.

AGARWAL, A., NANDA, B. & MAITY, D. 2014. Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. *Construction and Building Materials,* 71**,** 610-617.

AHMAD, R., HAMID, R. & OSMAN, S. A. Effect of different curing conditions on compressive strength and durability of kenaf fibre reinforced blended cementitious composites. 2018 International Joint Conference on Metallurgical and Materials Engineering (JCMME 2018), 10-12 Dec. 2018, 2019 France. EDP Sciences, 03012 (7 pp.).

AHMED, W., KHUSHNOOD, R. A., MEMON, S. A., AHMAD, S., BALOCH, W. L. & USMAN, M. 2018. Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties. *Journal of Cleaner Production,* 184**,** 1016-1027.

AKINDAHUNSI, A. A. 2019. Investigation into the use of extracted starch from cassava and maize as admixture on the creep of concrete. *Construction and Building Materials,* 214**,** 659-667.

AKINDAHUNSI, A. A. & SCHMIDT, W. 2019. Effect of cassava starch on shrinkage characteristics of concrete. *African Journal of Science, Technology, Innovation and Development,* 11**,** 441-447.

AKINDAHUNSI, A. A. & UZOEGBO, H. C. 2015. Strength and Durability Properties of Concrete with Starch Admixture. *International Journal of Concrete Structures and Materials,* 9**,** 323-335.

AL NUMAN, B. S. & AHMED, J. K. Effect of Wood-Particles Aggregate Percentage on Some Physical Properties of Concrete. 1st International Conference on Materials Engineering and Characterization, ICMECh 2019, May 8, 2019 - May 10, 2019, 2019 Sankarapuram, Kanchipuram, Tamil Nadu, India. Institute of Physics Publishing.

ALAZHARI, M., SHARMA, T., HEATH, A., COOPER, R. & PAINE, K. 2018. Application of expanded perlite encapsulated bacteria and growth media for self-healing concrete. *Construction and Building Materials,* 160**,** 610-19.

ALI A. ALIABDO, A. E. M. A. E., HAZEM A. SALEM 2016. Effect of cement addition, solution resting time and curing characteristics on fly ash based geopolymer concrete performance. *Construction & Building Materials,* 123**,** 581-593.

ALJALAWI, N. M. F. Effect of sustainable palm fiber on high strength concrete properties. 2nd International Conference on Sustainable Engineering Techniques (ICSET 2019), 6-7 March 2019, 2019 UK. IOP Publishing, 022004 (4 pp.).

ALYOUSEF, R., ALABDULJABBAR, H., MOHAMMADHOSSEINI, H., MOHAMED, A. M., SIDDIKA, A., ALRSHOUDI, F. & ALASKAR, A. 2020. Utilization of sheep wool as potential fibrous materials in the production of concrete composites. *Journal of Building Engineering,* 30**,** 101216.

ALYOUSEF, R., ALDOSSARI, K., IBRAHIM, O., MUSTAFA, H. & JABR, A. 2019. Effect of sheep wool fiber on fresh and hardened properties of fiber reinforced concrete. *Int. J. Civ. Eng. Technol,* 10**,** 190-199.

ANOWAI, S. I., OLORUNMEYE, P. & JOB, F. 2017. Durability properties of banana fibre reinforced fly ash concrete.

AWOYERA, P. & BABALOLA, O. 2015. Influence of steel and bamboo fibres on mechanical properties of high strength concrete. *Journal of Materials and Environmental Science,* 6**,** 3634-3642.

BABAFEMI, A. J., KOLAWOLE, J. T. & OLALUSI, O. B. 2019. mechanical and durability properties of coir fibre reinforced concrete. *Journal of Engineering Science and Technology,* 14**,** 1482-1496.

BAHURUDEEN, A., KANRAJ, D., V, G. D. & SANTHANAM, M. 2015. Performance evaluation of sugarcane bagasse ash blended cement in concrete. *Cement and Concrete Composites,* 59**,** 77 - 88.

BARNAT-HUNEK, D., SZYMAŃSKA-CHARGOT, M., JAROSZ-HADAM, M. & ŁAGÓD, G. 2019. Effect of cellulose nanofibrils and nanocrystals on physical properties of concrete. *Construction and Building Materials,* 223**,** 1-11.

BINICI, H., AKSOGAN, O., SEVINC, A. & CINPOLAT, E. 2015. Mechanical and radioactivity shielding performances of mortars made with cement, sand and egg shells. *Construction & Building Materials,* 93**,** 1145-1150.

BOIX, E., GINEAU, E., NARCISO, J. O., HÖFTE, H., MOUILLE, G. & NAVARD, P. 2020. Influence of chemical treatments of miscanthus stem fragments on polysaccharide release in the presence of cement and on the mechanical properties of bio-based concrete materials. *Cement and Concrete Composites,* 105**,** 103429.

BUNDUR, Z. B., SUNGWOO, B., KIRISITS, M. J. & FERRON, R. D. 2017. Biomineralization in Self-Healing Cement-Based Materials: Investigating the Temporal Evolution of Microbial Metabolic State and Material Porosity. *Journal of Materials in Civil Engineering,* 29**,** 04017079 (8 pp.).

CHABANNES, M., NOZAHIC, V. & AMZIANE, S. 2015. Design and multi-physical properties of a new insulating concrete using sunflower stem aggregates and eco-friendly binders. *Materials and Structures/Materiaux et Constructions,* 48**,** 1815-1829.

CHACKO, R., HEMA, S. & VADIVEL, M. 2016. Experimental studies on coconut fibre and banana fibre reinforced concrete. *International Journal of Modern Trends in Engineering and Science,* 3**,** 208-211.

CHIN, C. S. & NEPAL, B. 2019. Material Properties of Agriculture Straw Fibre-Reinforced Concrete. *Ecological Wisdom Inspired Restoration Engineering.* Springer.

CHINDASIRIPHAN, P., YOKOTA, H. & PIMPAKAN, P. 2020. Effect of fly ash and superabsorbent polymer on concrete self-healing ability. *Construction and Building Materials,* 233.

CHOUHAN, R. K., MUDGAL, M., BISARYA, A. & SRIVASTAVA, A. K. 2018. Rice-husk-based superplasticizer to increase performance of fly ash geopolymer concrete. *Emerging Materials Research,* 7**,** 169-177.

CUENCA, E. & FERRARA, L. 2020. Fracture toughness parameters to assess crack healing capacity of fiber reinforced concrete under repeated cracking-healing cycles. *Theoretical and Applied Fracture Mechanics,* 106.

D. GOWSIKA, S. S., K. SARGUNAN 2014. Experimental Investigation of Egg Shell Powder as Partial Replacement with Cement in Concrete. *International Journal of Engineering Trends and Technology (IJETT),* 14**,** 4.

DE KLERK, M. D., KAYONDO, M., MOELICH, G. M., DE VILLIERS, W. I., COMBRINCK, R. & BOSHOFF, W. P. 2020. Durability of chemically modified sisal fibre in cement-based composites. *Construction and Building Materials,* 241.

DHIR, D. K., RASHIDI, A., BOGYO, G., RYDE, R., PAKPOUR, S. & MILANI, A. S. 2020. Environmental Durability Enhancement of Natural Fibres Using Plastination: A Feasibility Investigation on Bamboo. *Molecules,* 25**,** 474.

DU, W., YU, J., HE, B., HE, Y., HE, P., LI, Y. & LIU, Q. 2020. Preparation and characterization of nano-SiO2/paraffin/PE wax composite shell microcapsules containing TDI for self-healing of cementitious materials. *Construction and Building Materials,* 231.

EDE, A. N., OSHOGBUNU, O., OLOFINNADE, O. M., JOLAYEMI, K. J., OYEBISI, S. O., MARK, O. G. & AWOYERA, P. O. Effects of bamboo fibers and limestone powder on fresh properties of self-compacting concrete. 10th International Structural Engineering and Construction Conference, ISEC 2019, May 20, 2019 - May 25, 2019, 2019 Chicago, IL, United states. ISEC Press, American Concrete Institute; American Institute of Steel Construction; Architectural Institute of Japan; Japan Concrete Institute; Japan Society of Civil Engineers.

EL MESSIRY, M. & FADEL, N. 2019. Tailoring the Mechanical Properties of Jute Woven/Cement Composite for Innovation in the Architectural Constructions.

FAN WU, C. L., LIANWEI ZHANG, YONGHU LU, YUANJUN MA 2018. Comparative study of carbonized peach shell and carbonized apricot shell to improve the performance of lightweight concrete. *Construction & Building Materials,* 188**,** 758-771.

FAPOHUNDA, C., AKINBILE, B. & OYELADE, A. 2018. A Review of the Properties, Structural Characteristics and Application Potentials of Concrete Containing Wood

Waste as Partial Replacement of one of its Constituent Material. *YBL Journal of Built Environment,* 6**,** 63-85.

FERAS TAJRA, M. A. E., CHRISTIAN LEHMANN, DIETMAR STEPHAN 2019. Properties of lightweight concrete made with core-shell structured lightweight aggregate. *Construction & Building Materials,* 205**,** 39-51.

FERRARA, G., CAGGEGI, C., GABOR, A. & MARTINELLI, E. Flax Textile Reinforced Mortars: Experimental Characterization and Structural Behavior. International Congress on Engineering and Sustainability in the XXI Century, 2019a. Springer, 885-892.

FERRARA, G., COPPOLA, B., DI MAIO, L., INCARNATO, L. & MARTINELLI, E. 2019b. Tensile strength of flax fabrics to be used as reinforcement in cement-based composites: experimental tests under different environmental exposures. *Composites Part B: Engineering,* 168**,** 511-523.

FERRARA, L. Self-healing cement-based materials: an asset for sustainable construction industry. FIB Conference: Sustainable Concrete: Materials and Structures, 10 April 2018, 2018 UK. IOP Publishing, 012007 (12 pp.).

FERREIRA, S. R., DE ANDRADE SILVA, F., LIMA, P. R. L. & TOLEDO FILHO, R. D. 2015. Effect of fiber treatments on the sisal fiber properties and fiber–matrix bond in cement based systems. *Construction and Building Materials,* 101**,** 730-740.

GASSNOVA. 2019. *CCS Norway* [Online]. CCSnorway.com: Gassnova. Available: https://ccsnorway.com/no/prosjektet/ [Accessed 26.01 2020].

GOH, L. D. & ZULKORNAIN, A. S. Influence of bamboo in concrete and beam applications. International Conference on Nanomaterials: Science, Engineering and Technology 2019,, 2019 Penang Island, Malaysia. Institute of Physics Publishing.

GRĂDINARU, C. M., ŞERBĂNOIU, A. A., BABOR, D. T., SÂRBU, G. C., PETRESCU-MAG, I. V. & GRĂDINARU, A. C. 2019. When agricultural waste transforms into an environmentally friendly material: The case of green concrete as alternative to natural resources depletion. *Journal of Agricultural and Environmental Ethics,* 32**,** 77-93.

GU, H. 2009. Tensile behaviours of the coir fibre and related composites after NaOH treatment. *Materials & Design,* 30**,** 3931-3934.

GUPTA, S., KUA, H. W. & KOH, H. J. 2018a. Application of biochar from food and wood waste as green admixture for cement mortar. *Science of the Total Environment,* 619-620**,** 419-435.

GUPTA, S., KUA, H. W. & LOW, C. Y. 2018b. Use of biochar as carbon sequestering additive in cement mortar. *Cement and Concrete Composites,* 87**,** 110-129.

HANZHOU YE, Y. Z., ZHIMING YU, JUN MU 2017. Effects of cellulose, hemicellulose and lignin on the morphology and mechanical properties of metakaolin-based geopolymer. *Construction and Building Materials,* 173**,** 10-16.

HAO, M., JUN, W. & HAOWEI, L. Study on corrosion behaviour of basalt fibre reinforced concrete under NaOH environment. 4th International Conference on Energy Equipment Science and Engineering, 28-30 Dec. 2018, 2019 UK. IOP Publishing, 052051 (6 pp.).

HARDJASAPUTRA, H., NG, G., URGESSA, G., LESMANA, G. & SIDHARTA, S. Performance of Lightweight Natural-fiber Reinforced Concrete. 6th International Conference of Euro Asia Civil Engineering Forum (EACEF 2017), 22-25 Aug. 2017, 2017 France. EDP Sciences, 01009 (6 pp.).

HISSEINE, O. A. 2019. Nano-engineering concrete properties for enhanced performance.

HISSEINE, O. A., WILSON, W., SORELLI, L., TOLNAI, B. & TAGNIT-HAMOU, A. 2019. Nanocellulose for improved concrete performance: a macro-to-micro investigation for disclosing the effects of cellulose filaments on strength of cement systems. *Construction and Building Materials,* 206**,** 84-96.

IEA, I. E. A.-. 2018. Technology Roadmap - Low-Carbon Transition in the Cement Industry, IEA Paris.

JECCOMPOSITES. 2011. *Kenaf, a fibre for the future: the Harusmas experience* [Online]. Available: http://www.jeccomposites.com/knowledge/international-composites-news/kenaf-fibre-future-harusmas-experience [Accessed].

JIANG, L., JIA, G., JIANG, C. & LI, Z. 2020. Sugar-coated expanded perlite as a bacterial carrier for crack-healing concrete applications. *Construction and Building Materials,* 232.

JIN, C., YU, R. & SHUI, Z. 2018. Fungi: A Neglected Candidate for the Application of Self-Healing Concrete. *Frontiers in Built Environment,* 4.

JOHN, V. J. & DHARMAR, B. 2020. Influence of basalt fibers in the mechanical behavior of concrete—A review. *Structural Concrete*.

JONKERS, H. M. 2011. Bacteria-based self-healing concrete. *Heron,* 56**,** 5-16.

JONKERS, H. M., THIJSSEN, A., MUYZER, G., COPUROGLU, O. & SCHLANGEN, E. 2010. Application of bacteria as self-healing agent for the development of sustainable concrete. *Ecological engineering,* 36**,** 230-235.

JOYKLAD, P., SUPARP, S. & HUSSAIN, Q. 2019. Flexural Response of JFRP and BFRP Strengthened RC Beams. *International Journal of Engineering and Technology,* 11**,** 203-7.

JUNTAO, D., JUN, Z. & ZHAOHUA, D. 2017. Effect of Superabsorbent Polymer on the Properties of Concrete. *Polymers,* 9**,** 672 (17 pp.).

KARIM, M. R., ZAIN, M. F. M., JAMIL, M. & LAI, F. C. 2013. Fabrication of a non-cement binder using slag, palm oil fuel ash and rice

husk ash with sodium hydroxide. *Construction and Building Materials,* 49.

KARTHIK, A., SUDALAIMANI, K. & KUMAR, C. T. V. 2017a. Durability study on coal fly ash-blast furnace slag geopolymer concretes with bio-additives. *ceramics international,* 43.

KARTHIK, A., SUDALAIMANI, K. & KUMAR, C. T. V. 2017b. Investigation on mechanical properties of fly ash-ground granulated blast furnace slag based self curing bio-geopolymer concrete. *Construction & Building Materials,* 149**,** 338-349.

KHALIQ, W. & EHSAN, M. B. 2016. Crack healing in concrete using various bio influenced self-healing techniques. *Construction and Building Materials,* 102**,** 349-57.

KHELIFA, M. R., LEKLOU, N., BELLAL, T., HEBERT, R. L. & LEDESERT, B. A. 2018. Is alfa a vegetal fiber suitable for making green reinforced structure concrete? *European Journal of Environmental and Civil Engineering,* 22**,** 686-706.

KHUSHNOOD, R. A., AHMAD, S., RESTUCCIA, L., SPOTO, C., JAGDALE, P., TULLIAN, J.-M. & FERRO, G. A. 2016. Carbonized nano/microparticles for enhanced mechanical properties and electromagnetic interference shielding of cementitious materials.

KHUSHNOOD, R. A., QURESHI, Z. A., SHAHEEN, N. & ALI, S. 2020. Bio-mineralized self-healing recycled aggregate concrete for sustainable infrastructure. *Science of the Total Environment,* 703.

KOUTA, N., SALIBA, J., EL OIFI, B. & SAIYOURI, N. Study of the effect of flax fibers on the fracture behavior of earth concrete by simultaneous application of digital image correlation and acoustic emission. 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures, 2019. IA-FraMCoS.

KRIKER, A., BALI, A., DEBICKI, G., BOUZIANE, M. & CHABANNET, M. 2008. Durability of date palm fibres and their use as reinforcement in hot dry climates. *Cement and Concrete Composites,* 30**,** 639-48.

KRISHNAN, K. N., HARI, R. & MINI, K. M. Comparative Study on Strengthening of Concrete Structures using Natural and Artificial fibers. International Conference on Applied Physics, Power and Material Science, 5-6 Dec. 2018, 2019 UK. IOP Publishing, 012002 (5 pp.).

LAGOUIN, M., MAGNIONT, C., SENECHAL, P., MOONEN, P., AUBERT, J.-E. & LABOREL-PRENERON, A. 2019. Influence of types of binder and plant aggregates on hygrothermal and mechanical properties of vegetal concretes. *Construction and Building Materials,* 222**,** 852-871.

LAU, K.-T., HUNG, P.-Y., ZHU, M.-H. & HUI, D. 2018. Properties of natural fibre composites for structural engineering applications. *Composites Part B: Engineering,* 136**,** 222-233.

LEE, H., WONG, H. & BUENFELD, N. 2016. Self-sealing of cracks in concrete using superabsorbent polymers. *Cement and concrete Research,* 79**,** 194-208.

LV, L., GUO, P., LIU, G., HAN, N. & XING, F. 2020. Light induced self-healing in concrete using novel cementitious capsules containing UV curable adhesive. *Cement and Concrete Composites,* 105.

MAAGE, M. 2015. *Betong - regelverk, teknologi og utførelse*, Fagbokforlaget.

MAAGE, M. & NORHEIM, B. 2015. *Betong - regelverk, teknologi og utførelse*, Fagbokforlaget.

MAHALAKSHMI, V. & DEVI, P. S. 2019. Prediction of Mechanical and Durability Properties of Treated Natural Fibres Concrete. *International Journal of Engineering Science,* 21788.

MAHZABIN, S., LIM JEE, H., LIM SIONG, K. & JARGHOUYEH, E. N. Behaviour of kenaf fibre reinforced composite. 10th Asia Pacific Structural Engineering and Construction Conference 2018, 13-15 Nov. 2018, 2019 UK. IOP Publishing, 012006 (9 pp.).

MALASZKIEWICZ, D. & SZTUKOWSKA, M. Utilization of wastes from medium density fiberboards production as an aggregate for lightweight cement composite. 3rd Scientific Conference Environmental Challenges in Civil Engineering, ECCE 2018, April 23, 2018 - April 25, 2018, 2018 Opole, Poland. EDP Sciences.

MBUGUA, R., SALIM, R. & NDAMBUKI, J. 2015. Utilisation of Gum Acacia Karoo as set-retarding water-reducing admixture in cement mortar and concrete at optimum dosage. *Knowledge Exchange for Young Scientists (KEYS),* Proceedings of the 1st symposium**,** 97-101.

MENON, R. R., LUO, J., CHEN, X., ZHOU, H., LIU, Z., ZHOU, G., ZHANG, N. & JIN, C. 2019. Screening of Fungi for Potential Application of Self-Healing Concrete. *Sci Rep,* 9**,** 2075.

MIGNON, A., VERMEULEN, J., GRAULUS, G. J., MARTINS, J., DUBRUEL, P., DE BELIE, N. & VAN VLIERBERGHE, S. 2017. Characterization of methacrylated alginate and acrylic monomers as versatile SAPs. *Carbohydr Polym,* 168**,** 44-51.

MOHAJERANI, A., HUI, S.-Q., MIRZABABAEI, M., ARULRAJAH, A., HORPIBULSUK, S., KADIR, A. A., RAHMAN, M. T. & MAGHOOL, F. 2019. Amazing types, properties, and applications of fibres in construction materials. *Materials,* 12.

MOMOH, E. O. & OSOFERO, A. I. 2019. Behaviour of oil palm broom fibres (OPBF) reinforced concrete. *Construction and Building Materials,* 221**,** 745-761.

MUDA, Z. C., MOHD KAMAL, N. L., SYAMSIR, A., SHENG, C. Y., BEDDU, S., MUSTAPHA, K. N., THIRUCHELVAM, S., USMAN, F., ALAM, M. A., BIRIMA, A. H. & ZAROOG, O. S. Impact Resistance Performance of Kenaf Fibre Reinforced Concrete. 2nd International Conference on Advances in Renewable Energy and Technologies, ICARET 2016, February 23, 2016 - February 25, 2016, 2016 Putrajaya, Malaysia. Institute of Physics Publishing, Detik Aturan; Energy Institute; Tenaga Nasional.

MUTHUSAMY, K. & ZAMRI, N. A. 2014. POFA: A Potential Partial Cement Replacement Material in Oil Palm Shell Lightweight Aggregate Concrete. *Applied Mechanics and Materials,* 567**,** 446-50.

NEERAJA, T. S. R. B. D. 2016. Experimental study of natural admixture effect on conventional concrete and high volume class F flyash blended concrete. *Case Studies in Construction Materials,* 6**,** 43-62.

NINA M. SIGVARDSEN, L. M. O. 2019. Characterization of coal bio ash from wood pellets and low-alkali coal flyash and use as partial cement replacement in mortar. *Cement and Concrete Composites,* 95**,** 25-32.

OKEOLA, A. A., ABUODHA, S. O. & MWERO, J. 2018. Experimental Investigation of the Physical and Mechanical Properties of Sisal Fiber-Reinforced Concrete. *Fibers,* 6**,** 53 (16 pp.).

OLUWABUSAYO, O., MWERO, J. & KABUBO, C. 2019. Experimental Investigation of the Physical and Mechanical Properties of Cassava Starch Modified Concrete. *The Open Construction & Building Technology Journal,* 13.

PAGE, J., KHADRAOUI, F., BOUTOUIL, M. & GOMINA, M. 2017. Multi-physical properties of a structural concrete incorporating short flax fibers. *Construction and Building Materials,* 140**,** 344-353.

PARISA SETAYESH GAR, N. S., VIVEK BINDIGANAVILE 2017. Sugar cane bagasse ash as a pozzolanic admixture in concrete for resistance to sustained elevated temperatures. *Construction & Building Materials,* 153**,** 929-936.

RAADE, G. 2019. *In:* LEKSIKON, F. S. N. (ed.) *Store Norske Leksikon.*

RAJCZAKOWSKA, M., NILSSON, L., HABERMEHL-CWIRZEN, K., HEDLUND, H. & CWIRZEN, A. 2019. Does a High Amount of Unhydrated Portland Cement Ensure an Effective Autogenous Self-Healing of Mortar? *Materials (Basel),* 12.

ROIG-FLORES, M., MOSCATO, S., SERNA, P. & FERRARA, L. 2015. Self-healing capability of concrete with crystalline admixtures in different environments. *Construction and Building Materials,* 86**,** 1-11.

RUMBAYAN, R., SUDARNO & TICOALU, A. A study into flexural, compressive and tensile strength of coir-concrete as sustainable building material. 4th International Conference on Sustainable Civil Engineering Structures and Construction Materials, SCESCM 2018, September 5, 2018 - September 7, 2018, 2019 Yogyakarta, Indonesia. EDP Sciences.

SABARISH, K., PAUL, P. & JONES, J. 2019. An experimental investigation on properties of sisal fiber used in the concrete. *Materials Today: Proceedings*.

SABATHIER, V., MAGNIONT, C., ESCADEILLAS, G. & JUAREZ, C. A. 2017. Flax and hemp fibre reinforced pozzolanic matrix: evaluation of impact of time and natural weathering. *European Journal of Environmental and Civil Engineering,* 21**,** 1403-1417.

SAI, P. P., MURALI, K., KUMAR, G. S. & TEJA, K. V. 2018. Study on properties of natural fibre reinforced concrete made with coconut shells and coir fibre. *International Journal of Civil Engineering and Technology,* 9**,** 416-422.

SEYED ALIREZA ZAREEI, F. A., NASROLLAH BAHRAMI 2018. Microstructure, strength, and durability of eco-friendly concretes containing sugarcane bagasse ash. *Construction & Building Materials,* 184**,** 258-268.

SHEIKH KHALID, F., HERMAN, H. S. & AZMI, N. B. Properties of Sugarcane Fiber on the Strength of the Normal and Lightweight Concrete. 2016 International Symposium on Civil and Environmental Engineering, ISCEE 2016, December 5, 2016 - December 6, 2016, 2017 Melaka, Malaysia. EDP Sciences.

SINGH, H. & GUPTA, R. 2020. Cellulose fiber as bacteria-carrier in mortar: Self-healing quantification using UPV. *Journal of Building Engineering,* 28.

SINGH, L. P., BISHT, V., ASWATHY, M. S., CHAURASIA, L. & GUPTA, S. 2018. Studies on performance enhancement of recycled aggregate by incorporating bio and nano materials. *Construction and Building Materials,* 181**,** 217-26.

SISMAN, C. B. & GEZER, E. 2013. Sunflower seed waste as lightweight aggregate in concrete production. *International Journal of Environment and Waste Management,* 12**,** 203-12.

STEVULOVA, N., CIGASOVA, J., SCHWARZOVA, I., SICAKOVA, A. & JUNAK, J. 2018. Sustainable bio-aggregate-based composites containing hemp hurds and alternative binder. *Buildings,* 8**,** 25.

STROEVEN, P., BUI, D. D. & SABUNI, E. 1999. Ash of vegetable waste used for economic production of low to high strength hydraulic binders. *Fuel,* 78**,** 153-159.

SULIMAN, N. H., ABDUL RAZAK, A. A., MANSOR, H., ALISIBRAMULISI, A. & AMIN, N. M. Concrete using sawdust as partial replacement of sand : Is it strong and does not endanger health ? International Conference on Sustainable Civil Engineering Structures and Construction Materials (SCESCM 2018), 5-7 Sept. 2018, 2019 France. EDP Sciences, 01015 (6 pp.).

SUN, B., WU, H., SONG, W., LI, Z. & YU, J. 2019. Design methodology and mechanical properties of Superabsorbent Polymer (SAP) cement-based materials. *Construction and Building Materials,* 204**,** 440-449.

SUNG-HOON KANG, S.-G. H., JUHYUK MOON 2019. The use of rice husk ash as reactive filler in ultra-high performance concrete. *Cement and Concrete Research,* 115**,** 389-400.

SYED MOHSIN, S. M., BAARIMAH, A. O. & JOKHIO, G. A. Effect of kenaf fiber in reinforced concrete slab. International Conference on Innovative Technology, Engineering and Sciences 2018, iCITES 2018, March 1, 2018 - March 2, 2018, 2018 Pekan, Pahang, Malaysia. Institute of Physics Publishing, Intel Malaysia; SCANIA Malaysia; Tourism Pahang.

TZIVILOGLOU, E., VAN TITTELBOOM, K., PALIN, D., WANG, J., SIERRA-BELTRÁN, M. G., ERŞAN, Y. Ç., MORS, R., WIKTOR, V., JONKERS, H. M. & SCHLANGEN, E. 2016. Bio-based self-healing concrete: from research to field application. *Self-healing Materials.* Springer.

UNITEDNATIONS. 2015. *Sustainable development goals* [Online]. https://www.un.org/sustainabledevelopment/: United Nations. Available: https://www.un.org/sustainabledevelopment/ [Accessed 27.04.2020 2020].

VINCIGUERRA, A. L., INCERTI, A., BURATTI, N., MANZI, S., RAMBALDI, E., MAZZOTTI, C. & BIGNOZZI, M. C. New sustainable binders based on waste valorization for civil engineering applications. 2nd International Workshop on Durability and Sustainability of Concrete Structures, DSCS 2018, June 6, 2018 - June 7, 2018, 2018 Moscow, Russia. American Concrete Institute, ACI Committee 130; ACI Committee 201; ACI Committee 544; ACI Committee 549; American Concrete Institute (ACI); et al.

WANG, J., JONKERS, H. M., BOON, N. & DE BELIE, N. 2017. Bacillus sphaericus LMG 22257 is physiologically suitable for self-healing concrete. *Appl Microbiol Biotechnol,* 101**,** 5101-5114.

WANG, L., CHEN, L., C.W.TSANG, D., GUO, B., YANG, J., SHEN, Z., HOU, D., OK, Y. S. & POON, C. S. 2020. Biochar as green additives in cement-based composites with carbon dioxide curing. *Journal of Cleaner Production,* 258.

WEILAI ZENG, Y. Z., CHI SUN POON, ZHANGYAO FENG, ZHENMEI LU, SURENDRA P. SHAH 2018. Using microbial carbonate precipitation to improve the properties of recycled aggregate. *Construction and Building Materials,* 228.

WIKTOR, V. & JONKERS, H. M. 2011. Quantification of crack-healing in novel bacteria-based self-healing concrete. *Cement and Concrete Composites,* 33**,** 763-770.

YAN, L., CHOUW, N., HUANG, L. & KASAL, B. 2016. Effect of alkali treatment on microstructure and mechanical properties of coir fibres, coir fibre reinforced-polymer composites and reinforced-cementitious composites. *Construction and Building Materials,* 112**,** 168-182.

YAN, Y., OUZIA, A., YU, C., LIU, J. & SCRIVENER, K. L. 2020. Effect of a novel starch-based temperature rise inhibitor on cement hydration and microstructure development. *Cement and Concrete Research,* 129.

ZAKARIA, M., AHMED, M., HOQUE, M. & SHAID, A. 2018. A Comparative Study of the Mechanical Properties of Jute Fiber and Yarn Reinforced Concrete Composites.

ZHANG, H., WANG, W., LI, Q., TIAN, Q., LI, L. & LIU, J. 2018. A starch-based admixture for reduction of hydration heat in cement composites. *Construction and Building Materials,* 173**,** 317-322.

ZHANG, J., MAI, B., CAI, T., LUO, J., WU, W., LIU, B., HAN, N., XING, F. & DENG, X. 2017. Optimization of a Binary Concrete Crack Self-Healing System Containing Bacteria and Oxygen. *Materials (Basel),* 10.

ZHANG, J., ZHAO, C., ZHOU, A., YANG, C., ZHAO, L. & LI, Z. 2019. Aragonite formation induced by open cultures of microbial consortia to heal cracks in concrete: Insights into healing mechanisms and crystal polymorphs. *Construction and Building Materials,* 224**,** 815-822.

# 7 Attachments

Attachment 1: Draft_article_Bio-based materials for sustainable concrete