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A review on application of bio-based materials to make more sustainable concrete

This review explores bio-based materials that may mitigate the effects of climate change from the concrete industry. The results implicate that there is a range of possibilities, gains and challenges when it comes to bio-based materials in concrete.

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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 article presents an overview or a "state-of-the-art" of current research on the area of 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. It is based on 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.

INTRODUCTION

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 reduce 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.

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.

Concrete is a durable building material and generally offers great compressive strength, and high durability is a positive contribution to both society, economy and environment. 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. 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.

There are generally two solutions of self-healing that can occur in cementitious materials, autogenous and autonomous. 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 mechanisms. 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.

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.

REVIEW

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). 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, Lau et al., 2018). 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 (Lau et al., 2018). 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, Lau et al., 2018). 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)(Lau et al., 2018). 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, Lau et al., 2018). 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). Incorporating natural fibres in the concrete reduces workability of the fresh mix, because the increase in fibre content enhances the cohesiveness and internal resistance.

Bamboo: 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).

Sisal: 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). 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).

Coconut: 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). 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).

Jute: 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). 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 % (Joyklad 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).

Flax: 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., 2019a, Ferrara et al., 2019b, Sabathier et al., 2017). Fibres can absorb water 130 % of their dry mass, however absorption after 24hrs 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).

Banana: 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).

Kenaf: 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).

Sheep wool: 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).

Additives

Binders

Coal bio ash (CBA) is a by-product from power plants that has reorganized from coal to biomass. 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. Studies compared CFA and CBA, showed CBA contain more calcium oxide (CaO). Compressive strength was lower for CBA than CFA after 14 days, but after 28 days 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. 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 (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 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).

Additives

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 and may allow production under lower temperatures than pure GPC. When biomaterials are added GPC/FA mixture, slump test have shown an improvement of the workability. 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(Karthik et al., 2017a). This bio-additive contains gallic acid esters and large number of disaccharides and were used in study by Karthik et al. Mortar with FA, GCBS and 0.8 wt% bio-additives by the weight of aluminosilicate minerals. 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).

Experiences of bio-GPC for better shielding against chemical attacks showed combination by Terminal chebula and palm jaggery had superior durability characteristics when compared to other bio-additive combinations. The sample 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).

Admixtures

Rice-husk-based superplasticizer specially developed for GP systems, showed results of 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).

Biochar is generated from waste biomass by pyrolysis. 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), food waste (FWBC), mixed wood saw dust (MWBC) or rice waste products (RWBC) have been studied.

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. 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. Compared with plain mortar, the 2 wt% FWBC increased late sorptivity by 2.2 times (Gupta et al., 2018). Test samples of SCBA show different results, and the workability was reduced slightly and setting time was longer than compared with OPC. All mortars that include biochar showed lower flowability than control sample, and MWBC showed the lowest flowability (Gupta et al., 2018). Addition of biochar result in higher ductility, however flexural strength was not remarkably improved (Gupta et al., 2018). Flexural strength is dependent on the type of food waste the biochar is made from. A 42 % increase was given in one test based at hazelnut shell biochar (Khushnood et al., 2016). In lightweight concrete, SCBA showed results of increased compressive strength up to 15 wt%, but highest increased compressive strength was obtained by 10 wt%. The reaction SCBA showed as a cement replacement, was associated with pozzolanic actions (Parisa Setayesh Gar, 2017, Gupta et al., 2018). Addition of biochar result in higher ductility, however flexural strength was not remarkably improved (Gupta et al., 2018). Flexural strength is dependent on the type of food waste the biochar is made from. A 42 % increase was given in one test based at hazelnut shell biochar (Khushnood et al., 2016). In lightweight concrete, SCBA showed results of increased compressive strength up to 15 wt%, but highest increased compressive strength was obtained by 10 wt%. The reaction SCBA showed as a cement replacement, was associated with pozzolanic actions (Parisa Setayesh Gar, 2017).

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 (Bahurudeen et al., 2015).

Biochar 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).

Research investigating the use of starch as an admixture shows that starch led to increased setting time and reduced workability of the fresh mix, 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). The effect of different starch-based admixtures on cement hydration showed promising results. 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.

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. Studies of the radioactivity shielding performances in mortar with OPC, water, sand and ESP found to increase the radiation absorption coefficient. 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 (Binici et al., 2015).

Rice husk ash (RHA)
Observations have showed that fine particles of biochar from RHA may be successfully used as reactive filler and may improve density and internal curing (Gupta et al., 2018). Due to significantly improved mechanical performance it may be alternative for high strength concretes (Sung-Hoon Kang, 2019).

Aggregates

Wood
Sawdust increased workability and water absorption of the fresh mix, but within the maximal allowable ratio for construction materials. Tests showed 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. Sawdust concrete is free from harmful health contaminants, and no form of treatment other than air drying is done before use. Incorporating sawdust result in low density cement products, and the low thermal conductivity could improve the energy efficiency of buildings. One study shows 22 % reduced HVAC energy and 13 % reduced CO2 emissions (Suliman et al., 2019, Ahmed et al., 2018, Al Numan and Ahmed, 2019). Saw dust ash produced from incineration of wood and biomass may be used as a retarder (Fapohunda et al., 2018).
Wood waste can also be used as coarse aggregate. Test results have revealed 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 (Fapohunda et al., 2018).

Sunflower and corn
The study concludes that structural and insulating concrete can be produced to meet strength, resistance and insulation requirements (Sisman and Gezer, 2013, Chabannes et al., 2015). Mixes were tested with 50 % vegetal aggregates (corn cob and sunflower stalk) treated in sodium silicate solution, 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. In the case of compressive and splitting tensile strength, the best results were obtained (Grădinaru et al., 2019).

Core fruit shell
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, resulted carbonized shells from peach (CPS) and apricot (CAS), which 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 CPS nor CAS. It showed significantly decreased creep strain. Mechanical properties did increase compared to non-carbonized shells as aggregate. Results indicate CAS to be suitable for production of high-strength LWAC.

(Fan Wu, 2018). 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).

Recycled aggregates (RA)
A study examining the use of recycled MDF as aggregate in lightweight concrete resulted in the concrete having highly improved strength properties. The concrete proved to be sensitive to humid environments, with high 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 treatment is based at treatment of the surface of recycled aggregate from construction and demolition waste. The studies are based on use of two bacillus species, B cohnii (ureolytic) and B. megaterium (non-ureolytic). In concrete containing 25 % RAC, observation shows that 3 % nano silica significantly increased compressive strength, compared with concrete containing natural aggregate. 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).

Self-healing

Use of superabsorbent polymers (SAP) is a technique that aims to improve the current autogenous self-healing capacity in concrete by serving 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. 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).

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. 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. In this study 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 (Lee et al., 2016).

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).

SAP absorbs water when incorporating them into the cement mixture and 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).

The autonomous self-healing process is based on additives as carriers and healing agent to promote crack healing. Several studies have reported concerns about the bacteria`s survivability in cement-based materials and it is reported when adding bacterial spores directly to the cement that they remained viable for a period between 2 and 4 months. 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).

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 table 1. 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 (Du et al., 2020).

Table 1 Compressive strength in concrete with incorporated microcapsules

	Average particle sizes	**Com-pressive 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

Khushnood et. al reports in their study that specimens with direct bacteria incorporation and recycled coarse aggregate (RCA) bacteria immobilizers and 50 % virgin fine aggregate led to an increase in strength. The method with pre-soaking of recycled coarse aggregate in microbial solution 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 with direct bacteria incorporation and recycled coarse aggregate (RCA) bacteria immobilizers and 50 % virgin fine aggregate 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 of pre-soaked recycled coarse aggregate in microbial solution. 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)

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. Light weight aggregates were not as efficient with a crack sealing at 0.61 mm 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) protected by a low-alkaline shell of potassium magnesium phosphate cement as a carrier compound. The w/c-ratio was 0.6 and Bacillus cohnii was used as a healing agent. The expanded perlite without a protective shell achieved a crack sealing at 0.27 mm (Jiang et al., 2020). Another study reports a similar crack sealing, with a maximum value of 1.22 mm after 28 days of healing by using expanded perlite as a carrier compound and a non-ureolytic pure culture of the bacteria Bacillus cohnii. 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 crack sealing was performed from the anoxic bacteria culture was induced by 82 % aragonite and 18 % calcite. The w/c-ratio was 0.4. 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).

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).

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).

DISCUSSION

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.

The best results from strength testing of each fibre can be seen in *(Figure 1),(Figure 2) and (Figure 3).*

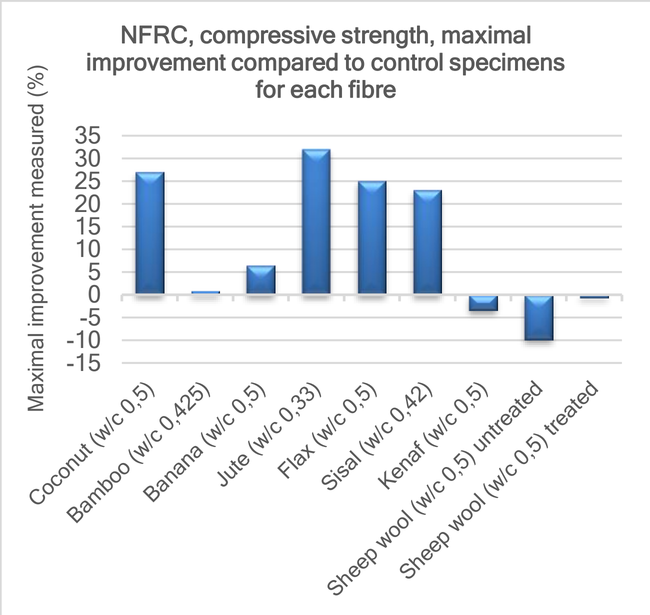

Figure 1 *Compressive strength, natural fibre reinforcement concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Goh and Zulkornain, 2019), Banana (Chacko et al., 2016), Jute (Zakaria et al., 2018), Flax (Sabathier et al., 2017), Sisal (Sabarish et al., 2019), Kenaf (Mahzabin et al., 2019), Sheep wool (Alyousef et al.,*

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 1).* All these samples have cured under similar conditions, which eliminates the effect different curing conditions is to the result.

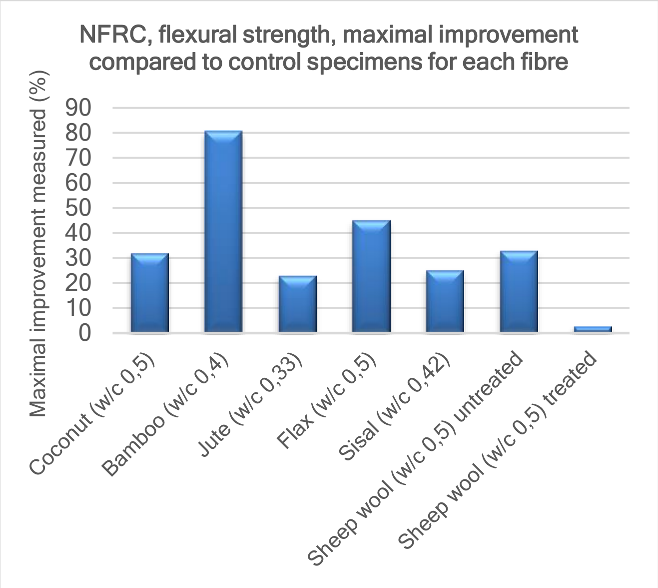

Figure 2 Flexural strength, natural fibre reinforced concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Goh and Zulkornain, 2019), Banana (Chacko et al., 2016), Jute (Zakaria et al., 2018), Flax (Sabathier et al., 2017), Sisal (Sabarish et al., 2019), Kenaf (Mahzabin et al., 2019), Sheep wool (Alyousef et al., 2020)

The flexural strength *(Figure 2)* 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.

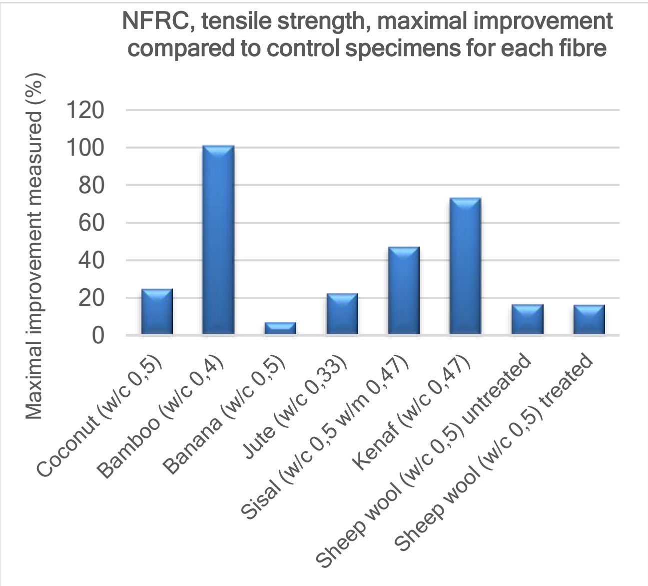

Figure 3 Tensile strength, natural fibre reinforced concrete. Maximal improvement compared to control specimens. Coconut (Mahalakshmi and Devi, 2019), Bamboo (Goh and Zulkornain, 2019), Banana (Chacko et al., 2016), Jute (Zakaria et al., 2018), Flax (Sabathier et al., 2017), Sisal (Sabarish et al., 2019), Kenaf (Mahzabin et al., 2019), Sheep wool (Alyousef et al., 2020)

The tensile strength *(Figure 3)* 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.

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 high 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.

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 high 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 large 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.

Additives, admixtures, binders and fillers

Binder

Coal Bio ash and rice husk ash show promising abilities for cement replacement and show pozzolanic behaviour. There is higher amount of Calcium Oxide (CaO) in CBA than FA and this increase the capacity to neutralize acid and result in higher buffer capacity than OPC. 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. 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. RHA shows interesting properties for further studies as cement replacement in mortar and as reactive filler, due to pozzolanic behaviour.

Additives
Geopolymer concrete require special curing conditions, and it requires prefabrication. Tests show that in an alkali medium, the interactions between bio-additives and GP may lead to decrease in required curing temperature and open for wide range of applications. All bio-additives showed increased workability and the additives that showed the best mechanical strength was combination of

powder Terminal Chebula and palm jaggery. In combination with FA and GCBS, results show 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 4).*

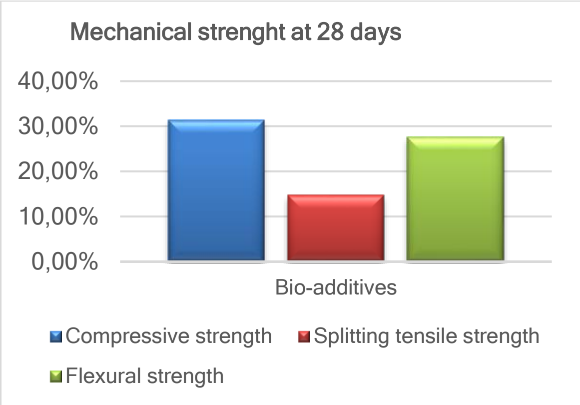

Figure 4 Improved mechanical properties of Bio-additives Terminalia chebula and palm jaggery, compared with GPC (Karthik et al., 2017b)

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.

Rice husk can be utilized as a plasticizer for GPC.

Admixtures

Compressive strength increased in all type of BC except RWBC. SCBA showed also promising result of the compressive strengths in LWC. 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% as shown in *Figure 5.* Amount of MWBC over 5 wt% the strengths were remarkably reduced.

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.

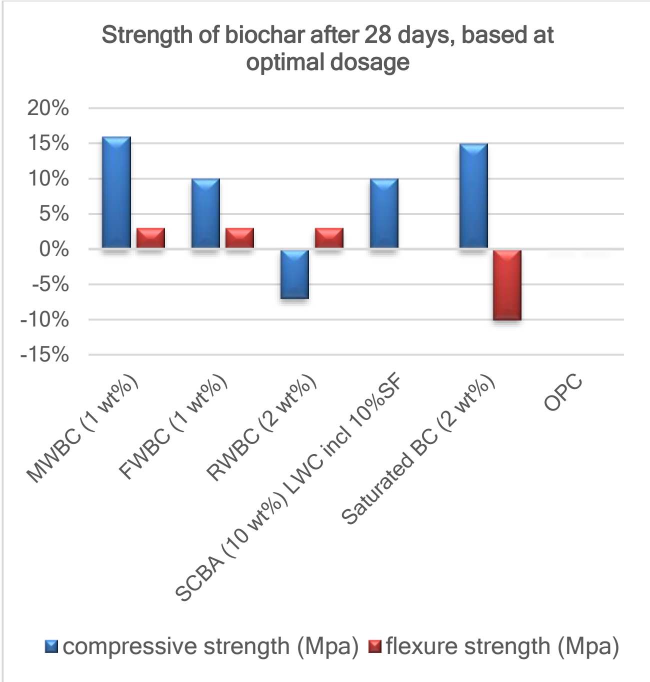

Figure 5 Strength of biochar based on optimal dosage, w/c 0.4, OPC as control sample, MWBC, FWBC, RWBC (Gupta et al., 2018a), SCBA(Seyed Alireza Zareei, 2018), saturated BC (Gupta et al., 2018b)

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. BC may have the potential to be successfully used as a carbon sequestering admixture in concrete. Initial trials show catalytic capacity.

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.

Filler

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

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. RHA is a feasible alternative for high strength concretes, but it has shown higher costs for preparation of the material before use in concrete.

Aggregate

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

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.

Core fruit shell show many of the same abilities and with good strength properties it is suitable for high strength LWAC. 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.

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

Self-healing

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 crack sealing capacity is clearly limited. 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 initial crack width also plays a significant role to the crack sealing capacity (Cuenca and Ferrara, 2020, Roig-Flores et al., 2015). Presence of dispersed fibre reinforcement can control and limit crack width and could be favourable in a self-healing system but is not rendered in this study

The highest crack-sealing reviewed was 1.24 mm. It is shown that the natural autogenous 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.

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. 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.

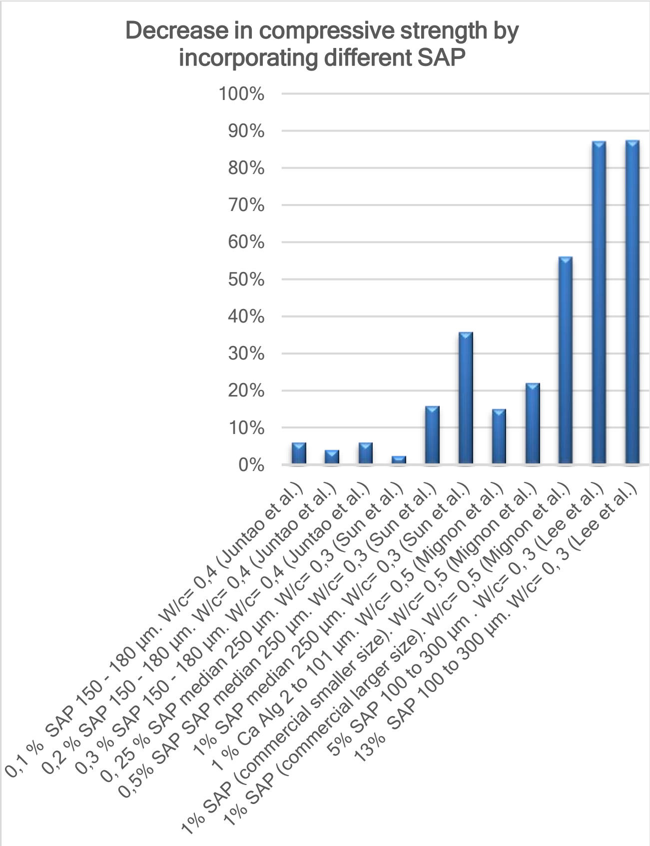

Figure 6 Decrease in compressive strength with SAP`s

The alginate beans (CaAlg) investigated by Mignon et al (Mignon et al., 2017) 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 autogenous self-healing in concrete. The technique is a cost-effective solution which enable it to a future commercialize.

The calcium precipitation of microorganisms is more efficient than the chemical precipitation contributing in autogenous self-healing with the highest value of crack sealing at 1.24 compared to the crack sealing at 0.84 mm shown in the blends with fly ash under perfect exposure condition mentioned earlier. In a bacterial self-healing concept calcium carbonate ($CaCO_3$) can be precipitated by bacteria by microbially induced calcium carbonate precipitation (MICP). The bacteria self-healing concept has been extendedly studied the last years. The system has a weakness concerning long-term self-healing efficacy. Limited biomineralized CaCO3 production by bacteria after introduction into the incompatible concrete matrix is a major challenge of this technology. To ensure the survivability 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. Two different techniques can be used in the autonomous healing system with microorganisms, capsulation or absorption.

When adding new elements to the concrete mix the mechanical properties can change. 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 (Du et al., 2020). 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.

The technique concerning encapsulation appears as detailed and complex and it can therefore be favorable 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.

The precipitation efficacy is also depending on the bacteria specie and the biological pathway for the precipitation. The highest crack sealing result revealed trough the review 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 2, sorted from the highest to lowest level.

Table 2 Comparison of crack sealing in different carrier compound, bacteria types and w/c-ratio sorted from high to low crack sealing. References 1.24 mm (Jiang et al., 2020), 1.22 mm (Zhang et al., 2019), 1.10 mm (Khushnood et al., 2020), 0.81 mm (Khaliq and Ehsan, 2016), 0.79 mm (Jiang et al., 2020), 0.79 mm (Zhang et al., 2019), 0.73 mm (Zhang et al., 2019)and 0.61 mm (Khaliq and Ehsan, 2016) Comparison of crack sealing in different carrier compound, bacteria types and w/c-ratio sorted from high to low crack sealing. References 1.24 mm (Jiang et al., 2020), 1.22 mm (Zhang et al., 2019) Comparison of crack sealing in different carrier compound, bacteria types and w/c-ratio sorted from high to low crack sealing. References 1.24 mm (Jiang et al., 2020), 1.22 mm (Zhang et al., 2019), 1.10 mm (Khushnood et al., 2020), 0.81 mm (Khaliq and Ehsan, 2016), 0.79 mm (Jiang et al., 2020), 0.79 mm (Zhang et al., 2019, Khushnood et al., 2020), 0.81 mm (Khaliq and Ehsan, 2016), 0.79 mm (Jiang et al., 2020), 0.79 mm (Zhang et al., 2019), 0.73 mm (Zhang et al., 2019)and 0.61 mm (Khaliq and Ehsan, 2016, Zhang et al., 2019)and 0.61 mm (Khaliq and Ehsan, 2016)

Crack sealing mm	Carrier compound	Bacteria type	W/c-ratio
1.24	Sugar-coated expanded perlite with potassium magnesium phosphate cement shell	Bacillus cohnii	0.6
1.22	Expanded perlite	Anoxic bacteria culture	0.4
1.10	Recycled coarse aggregate	Bacillus substilis	0.4
0.81	Graphite Nano platelets	Bacillus substilis	0.4
0.79	Sugar-coated expanded perlite with acidic sulfoaluminate cement shell	Bacillus cohnii	0.6
0.79	Expanded perlite	Bacillus cohnii	0.4
0.73	Expanded perlite	Bacillus cohnii	0.4
0.61	Light weight aggregates	Bacillus substilis	0.4

Khaliq and Ehsan (Khaliq and Ehsan, 2016) and Khushnood et al. (Khushnood et al., 2020) investigated bacterial self-healing with different carrier compounds and revealed that the crack sealing capacity is reduced by about 50 % for several of the samples at pre-cracking in older specimen. Further on, it has been reported no loss in viability for over six months when the bacteria spores were incorporated in the concrete (Jonkers, 2011) and it is also been reported live cells at 330 days (Tziviloglou et al., 2016). Out of this we can assume that it is possible to develop a long-term system with the right strain and a suitable carrier compound. 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 is fungi. Fungi is effective concerning calcium carbonate precipitation and can promote large amount within short time and it is therefore pointed out that the self-healing system with fungi may be more efficient than bacteria with a more rapid and long-lasting effect (Jin et al., 2018). Considering this, fungi appears as a possible preferred candidate in a self-healing system in concrete. At present it seems like it is a lack of investigations on this possibility as a self-healing system

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.

Another aspect that need attention is the cost efficacy a healing system based on microorganisms can offer. For example, the system with recycled coarse aggregate with Bacillus subtilis presents an increase at 119.4 % in cost compared with conventional concrete with the same 28 days compressive strength (Khushnood et al., 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 (Zhang et al., 2019). Developing of cost-efficient strain and cultivation system that can serve the self-healing purpose seems like crucial for future realization.

Another 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.

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.

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.

CONCLUSION

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.
- The research is lacking in many areas on NFR and considering the positive environmental impact of utilizing NFR, the value of research on this area is huge and should be prioritized. 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 are 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, 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.

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

• A cooperating self-healing system based on both autogenous and autonomous healing should be further investigated.

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