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CoRncrete: A corn starch based building material

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Highlights
- A novel material which uses corn starch as a binder and sand as filler.
- Rapidly hardening material gaining strength by heating at a relatively low temperature (<= 200˚C).
- CoRncrete has a compressive strength of up to 26MPa.
- Biodegradable and light-weight compared to traditional concrete and brick.

Abstract

Starch is a natural polymer which is commonly used as a cooking ingredient. The renewability and bio-degradability of starch has made it an interesting material for industrial applications, such as production of bioplastic. This paper introduces the application of corn starch in the production of a novel construction material, named CoRncrete. CoRncrete is formed by mixing corn starch with sand and water. The mixture appears to be self-compacting when wet. The mixture is poured in a mould and then heated in a microwave or an oven. This heating causes a gelatinisation process which results in a hardened material having compressive strength up to 26MPa. The factors affecting the strength of hardened CoRncrete such as water content, sand aggregate size and heating procedure have been studied. The degradation and sustainability aspects of CoRncrete are elucidated and limitations in the potential application of this material are discussed.

Keywords: Corn starch, construction material, gelatinisation, biopolymer, compressive strength

1. Introduction

Starch is an abundant biopolymer that is produced and stored in photosynthetic tissue of plants. It is a cheap and biodegradable polymer that is derived from renewable sources. These advantages make it an attractive material for food and non-food applications. Starch forms an important source of energy in human diet in form of bread, pasta and bakery products. In recent years, it has been used as a substitute of crude oil derived components in numerous chemical application such as plastic, detergent and adhesives [1]. It is also widely used in paper making and manufacturing of corrugated boards.

Starch is known as a semi-crystalline material which contains alternate crystalline and amorphous regions [2]. It is a polysaccharide consisting of a large number of glucose units linked together by $\alpha(1,4)$ bonds. It is a heterogeneous material consisting of linear (amylose) and branched (amylopectin) molecules [3]. The composition of starch is more or less universal with a major component of amylopectin (75%) and a minor component of amylose (25%) irrespective of its source [4].

In Europe, starch is mainly extracted from potatoes, wheat and maize. According to the Starch Europe Association [1], European Union (EU) starch production has increased from 8.7 million tonnes in 2004 to 10.5 million tonnes in 2014. The EU consumes about 9 million tonnes of starch, of which 61% is in food, 1% in feed and 38% is used in non-food applications, primarily paper making.

The application of starch extends to the building and construction industry where it has been used as a binder in thermally insulating composites [5-10], an admixture for viscosity modification in concrete [11-17], a modifier in asphalt [18] and retarder in the cement hydration process [19]. In the investigation on thermally insulating composites, researchers utilised natural fibres, such as hemp [5-7], sisal [8] and jute [9], with starch acting as a binder and improving the mechanical performance. In their investigation, Balčiūnas et al. [6] utilised hemp hurds and corn starch to build composites, with a compressive strength of up to 1.9 MPa. Whereas composites manufactured by Gacoin et al. [7], using hemp and wheat starch, had a maximum compressive strength of 2.1 MPa. Starch based Ether has been utilised by Isik and Ozkul [11] and Cappellari et al. [12] in concrete and mortar respectively to improve the rheological property of the mix. Vieira et al. [15] and Crépy et al. [17] utilised modified starch as the dispersing agent in self-compacting concrete. Al-Hadidy et al. [18] improved the moisture and temperature susceptibility of asphalt material by adding starch. Peschard et al. [19] showed that starch enhanced the retarding effect on hydration of cement. In all these aforementioned investigations, the rheological and gelatinisation properties have been exploited to improve the flow and binding properties of different materials. The use of corn starch and its derivatives are wide, and in fact, the possibility of producing starches with different chemical properties from corn starch has made it the most used starch for industrial applications [3]: 47.5% of starch products are based on corn starch [1].

When corn starch is mixed with water in sufficient quantity, it forms a non-Newtonian fluid. Suspensions of corn starch in water show shear thickening behaviour, which means that the suspension can resist rapid deformation, but when left unperturbed, it becomes a thin liquid. Starch granules are insoluble in cold water. When the starch granules are heated in the presence of water, a phase transition occurs. When sufficient water is present, this transformation, called gelatinisation, results in near-dissolution of the starch [20]. Gelatinisation is an irreversible process that includes granular swelling, native crystalline melting, and molecular solubilisation [21]. The temperature at which gelatinisation occurs is called the gelatinisation temperature.

This work focuses on the application of un-modified corn starch as a binder in a new construction material named CoRncrete. CoRncrete is formed by mixing water with corn starch and sand, and heating the mix in a microwave or oven. This heating process results in the formation of a hardened material. Figure 1 shows an overview of the production process of CoRncrete. An introductory video on how to make CoRncrete can be seen on YouTube [22]. The main objectives of the study, which is presented in this paper, was to determine the optimum mixture composition and heating procedure and to explain the physical behaviour of CoRncrete, with a focus on the factors affecting the compressive strength of the hardened material. Secondly, the durability with respect to water resistance and the environmental performance of CoRncrete are evaluated.
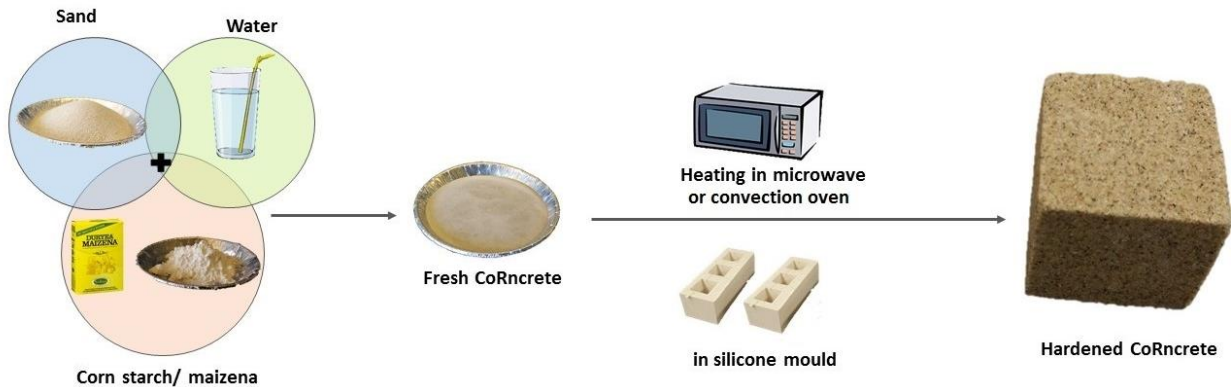

Fig. 1. Preparation of hardened CoRncrete by heating fresh CoRncrete (filled in a silicone mould) in a microwave or a convection oven.

2. Materials and Methods

2.1 Preparation of fresh CoRncrete

Fresh CoRncrete was prepared by mixing corn starch (Duryea Maizena, Unilever, Netherlands), sand of grain size 0.125-0.25mm (Sibelco, Netherlands) and tap water. Mixing was performed for 2 minutes at 50 RPM in an electric mixer (Model: KMM760, Kenwood, UK). Prior to electric mixing, corn starch and sand were manually mixed in order to prevent the clustering of wet corn starch particles in the electric mixer. A constant corn starch to sand dry-weight proportion of 1:5 (i.e. 16.6%) corn starch) has been adopted throughout this work based on preliminary test results (compressive strength) that were carried on CoRncrete prepared by mixing different proportions of corn starch and sand.

2.2 Physical behaviour of Fresh CoRncrete

2.2.1 Fallcone test

The fallcone test was performed on sand, corn starch and fresh CoRncrete to study the physical behaviour of the fresh CoRncrete mixture. The fallcone test is typically used in geotechnical engineering practice to determine the undrained shear strength of fine grained soils (clays or silts) and is one of the prescribed standard methods to determine the liquid limit. The liquid limit is one of the consistency limits which is used for the classification of fine grained soils. It is defined as the water content, which indicates an empirically defined boundary at which fine grained soils undergo a transition from a viscous liquid state to plastic solid state [23]. A recent study used this test to provide insight in the saturation dependent strength of unsaturated sand [24]. The test equipment consists of a standard cone with a cone tip angle of 30º and a mass of 80g, and a sample cup of internal diameter 55mm and 40mm height (capacity: 100ml). The samples were prepared by adding water in increments of 3.3%(wt.). In the case of only corn starch, equivalent increments of 20 wt.% of water were added to ensure a similar water to corn starch ratio, as in CoRncrete. The sample cup was filled in 3 layers, where each layer was tamped 10 times with a rubber capped steel rod. Excess material was flattened off along the rim and the weight was measured, which was used to calculate bulk density. The tip of the cone was lowered down to the top of material and released. Readings were taken to the nearest 0.1mm at 5, 10, 20 and 30 sec. A sample of approximately 30-50g from the middle of sample cup was then taken in a glass crucible for determination of the water content. The water content was determined by measuring the mass loss when heated at 105°C for 24h in an oven, and used to determine the dry density.

2.2.2 Proctor test

The Proctor test was carried out on the wet CoRncrete mixture and sand following the guidelines of BS 1377:part4:1990 [25]. The Proctor test is an extensively used laboratory compaction test to determine the relationship between dry density and water content for medium to fine grained geo-materials such as clay, silt and sand [25]. In this test, the soil particles are compacted by mechanical means, thereby increasing the dry density of soil. The obtained dry density depends on the amount of compaction energy applied and the amount of water present in the soil. The water content corresponding to maximum dry density is termed as the optimum water content. At this water content, maximum compaction is achieved (high packing density and minimum voids). The test setup consists of a compaction mould (1 litre capacity) and mechanical rammers. An adaptation was made to the code by compacting samples with lower energies, 22.1 kJ/m^3 (150g rammer with 20 cm drop height) and 51.5 kJ/m^3 (350g rammer with 20 cm drop height) as opposed to 595.5 kJ/m^3 (2500g rammer with 30 cm drop height). The samples were prepared by adding water in increments of 3.3%(wt.). The increment was changed to 1.5% when significant difference in bulk density of consecutive readings was observed. The prepared sample

was filled in the mould in 3 layers, where each layer was tamped 25 times with a rammer. Excess material was flattened off along the rim and the weight of the sample was measured from which the bulk density was calculated. The water content and the dry density of sample were then determined by heating a representative sample taken from the mould for 24h in an oven at 105°C.

2.3 Differential Scanning Calorimetry (DSC)

DSC was used to determine the gelatinisation temperatures (onset [T_o], peak [T_p] and end [T_e] temperatures) of fresh CoRncrete with 15% and 18% (wt.) water content, using a Perkin Elmer DSC 7 (Netherlands). DSC is a thermal analysis technique to measure the heat capacity of material with increasing temperature. In this technique, the amount of heat required to raise the temperature of a material at constant temperature rate is measured in comparison to a reference sample. DSC is a widely used technique to quantify the gelatinisation of starch [26]. A gold pan with a high pressure seal was utilised in order to prevent moisture loss from the sample. An empty stainless steel pan was used as the reference sample. The sample pans were heated in air at 5°C/min from 25°C to 200°C and later cooled at 5°C/min from 200°C to 25°C. A slow heating rate was adopted in order to prevent pressure built up inside the pan and temperature lag due to the higher conductivity of the gold pan.

2.4 Preparation of hardened CoRncrete

Hardened CoRncrete specimens of 40×40×40mm³ were prepared to study effect of water content, sand grain size and heating procedure on compressive strength. The fresh CoRncrete was placed in a casting mould and heated in the electric heating equipment in order to form a hardened CoRncrete (Fig.1). The casting mould was made with silicone rubber as it is flexible, easy to cast into the desired shape, withstand temperatures of up to 200°C [27] and allows microwaves to pass through it with little or no energy absorption. The moulds were filled in three layers, each layer was tamped 10-15 times with a silicone rubber capped steel rod as shown in Fig. 2. The extra material was trimmed off and the samples were taken immediately to the heating source. Two heating methods were adopted: microwave and convection oven heating. In case of the microwave heating method, the sample was placed in the microwave (Model: RFS511 MP, 2450MHz, 230V, output power 1100W, Amana refrigeration Inc., USA). The specimens were heated for 5 min, the first 1.5 min in thaw mode (19.8 kJ total energy) and the next 3.5 min in high power mode (231 kJ total energy). This heating scheme was selected based on different combinations tried in the preliminary study. A surcharge of 2kg was placed on the sample (Fig. 2) to prevent deformation and subsequent cracking of CoRncrete which was observed during preliminary tests at these high rates of heating. In the oven heating method, the specimens were heated at 105°C for 24h in an industrial oven (Model 800, Memmert GmbH, Germany). No surcharge was placed over the specimens in the oven as no significant deformation was observed during heating. Once the heating of the specimens was finished, the mould was taken out. The specimens were detached and kept at room temperature (20°C) to cool. After 30 minutes, the specimens were sealed in a plastic bag to prevent further interaction with the environment.

To study the effect of water content on CoRncrete, in total 12 categories of samples (6 microwave+6 oven) were prepared with water contents ranging from 10% to 20%. To study the effect of sand grain size on strength, 8 categories of samples (4 microwave+4 oven) were prepared with sand grain size of 0.125-0.25mm, 0.25-0.50mm, 0.50-1.0mm and 1.0-2.0mm (Sibelco, Netherlands). To study the effect of duration of heating on the strength of CoRncrete in a microwave, 5 categories of samples with the same composition were prepared. The duration of heating was different for each category. In all the experiments, 3 cubic specimens for each category were prepared and tested in order to determine the average compressive strength of the material.
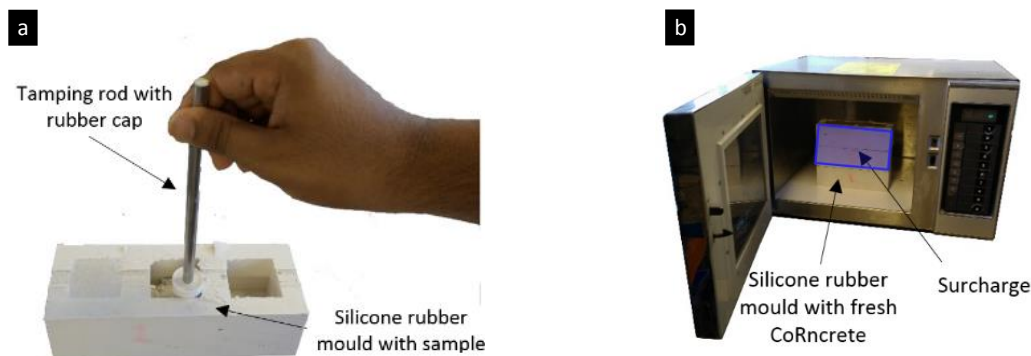

Fig. 2. Preparation of sample in silicone rubber mould and heating. (a) Filling the mould in 3 layers and compacting each layer with silicone rubber capped steel rod and (b) Mould placed in the microwave with surcharge.

2.5 Environmental Scanning Electron Microscopy (ESEM)

ESEM was used to analyse the microstructural characteristics of the corn starch and CoRncrete samples (Table 1) using a Philips XL-30 (Netherlands) ESEM, in vacuum at 20°C. Scans were made at 125x and 1000x magnification.

Sample	Water content [%]	Description
Corn starch	10.8	Water content of commercially available Maizena (Unilever, Netherlands)
CoRncrete	16.66	Partially heated in microwave [1.5min (thaw)=19.8kJ]
	16.66	Completely heated in microwave [1.5(thaw)+3.5(high power)=250.8 kJ]
	16.66	Heated in oven at 105°C for 24h.
	15	DSC sample heated in a confined chamber
	18	DSC sample heated in a confined chamber

2.6 Compressive strength testing

The CoRncrete specimens were tested in a compression testing machine (Model: E161PN114, Matest, Italy) according to NEN-EN 196-1:2005 [28]. The loading parameters used were: loading rate=2.4kN/sec, start load=0.1kN and stop load=25% of the maximum load. The specimens were prepared and tested in triplicates and the results were expressed as average unconfined compressive strength (MPa).

3. Result and discussion

This research is mainly divided into 3 parts: the physical behaviour of fresh CoRncrete, heat induced transformation of fresh CoRncrete to hardened CoRncrete and mechanical and microstructural characterization of hardened CoRncrete. The behaviour of fresh CoRncrete was studied by performing the fallcone and proctor tests in order to understand the phase transition of fresh CoRncrete and its compaction behaviour, with addition of water. The heat induced transformation was investigated by the thermal and microstructural characterisation of CoRncrete. Finally, the effect of water content, sand grain size, and heating duration on compressive strength of hardened CoRncrete was evaluated. The article ends with a comprehensive note on sustainability and durability of CoRncrete, which might influence the potential application of CoRncrete.

3.1 Determination of shear strength behaviour, dry density and optimum water content

The fallcone test results are presented in Fig. 3. As shown in Fig. 3(a), compacting dry sand resulted in the highest dry density of about 1550 kg/m³, but a relatively large penetration depth, indicating a relatively low shear strength. When adding 3.3% water to the sand, the dry density significantly reduced to reach a minimum of almost 1200 kg/m³. Also the penetration depth significantly reduced. The capillary tension of the water film between the sand grains acts as apparent cohesion and increases the shear strength. Further water addition caused a gradual increase in dry density, reaching an optimum at 16.8% and a gradual decrease in penetration depth. At a water content of 26%, the sand approached saturation at which compaction energy is taken up by the water and capillary tension is reduced, resulting in an increased penetration. For all tests on sand the penetration was immediate and did not show time dependent behaviour.

Corn starch (Fig. 3(b)) showed a significantly lower dry density than sand ranging from 560 to 700 kg/m³ for the whole range of water contents, which is partly due to a lower specific density, (i.e. typically 1.5 compared with 2.65 for quartz sand) but also due to a higher void ratio. Dry corn starch also exhibited a lower penetration depth than dry sand, possibly due to a smaller grain size and more interlocking between particles. With an increase in water content up to 47.5%, starch particles swell as they bind the water and show significant cohesion resulting in a reduction in dry density and an increase in shear strength as indicated by the very low penetration depths. With further increase in water content from 81 up to 91%, the corn starch water mixture undergoes a phase transition in which the cone penetration increased in time. This time-dependent penetration clearly demonstrated the non-newtonian viscous behaviour. A similar phase transition was observed in a study carried out by Crawford.et al. [29], dense clusters of suspended corn starch particles were formed at water contents around 90.5%, resulting in a high viscosity. With an increase in water content above 91%, the dense clusters of corn starch change into a suspension of corn starch particles in water, which resulted in a rapid penetration of the cone to the bottom of the cup, indicating a very low shear strength.

The results for fresh CoRncrete are shown in Fig. 3(c). When the water content increased from 0 to 10% a decrease in dry density was observed for the CoRncrete mixture similar to sand, but the dry density values were significantly lower than for sand. The penetration depth is in the same range of sand, but higher than starch. The behaviour is schematically explained in Fig. 3(d1): When dry the corn starch has no cohesive force, thus starch particles are free to move relative to the sand particles. With increase in water content, the water is adheres to the corn starch particles, which may become cohesive, but the cohesive strength is less than for pure starch due to the presence of the large sand fraction (Fig. 3(d2)). With increasing water content from 10.4 to 13.7% the cohesive strength was reduced as indicated by an increase in the penetration depth. From 16.6% to 20.2% water content, the penetration became time-dependent, indicating a phase change of corn starch in fresh CoRncrete (Fig. 3 (d3)). At a water content of 18% the highest dry density was obtained. Above this water content, the mixture did not show any shear strength as the fallcone dropped rapidly to the bottom of the cup (Fig. 3(d4)).
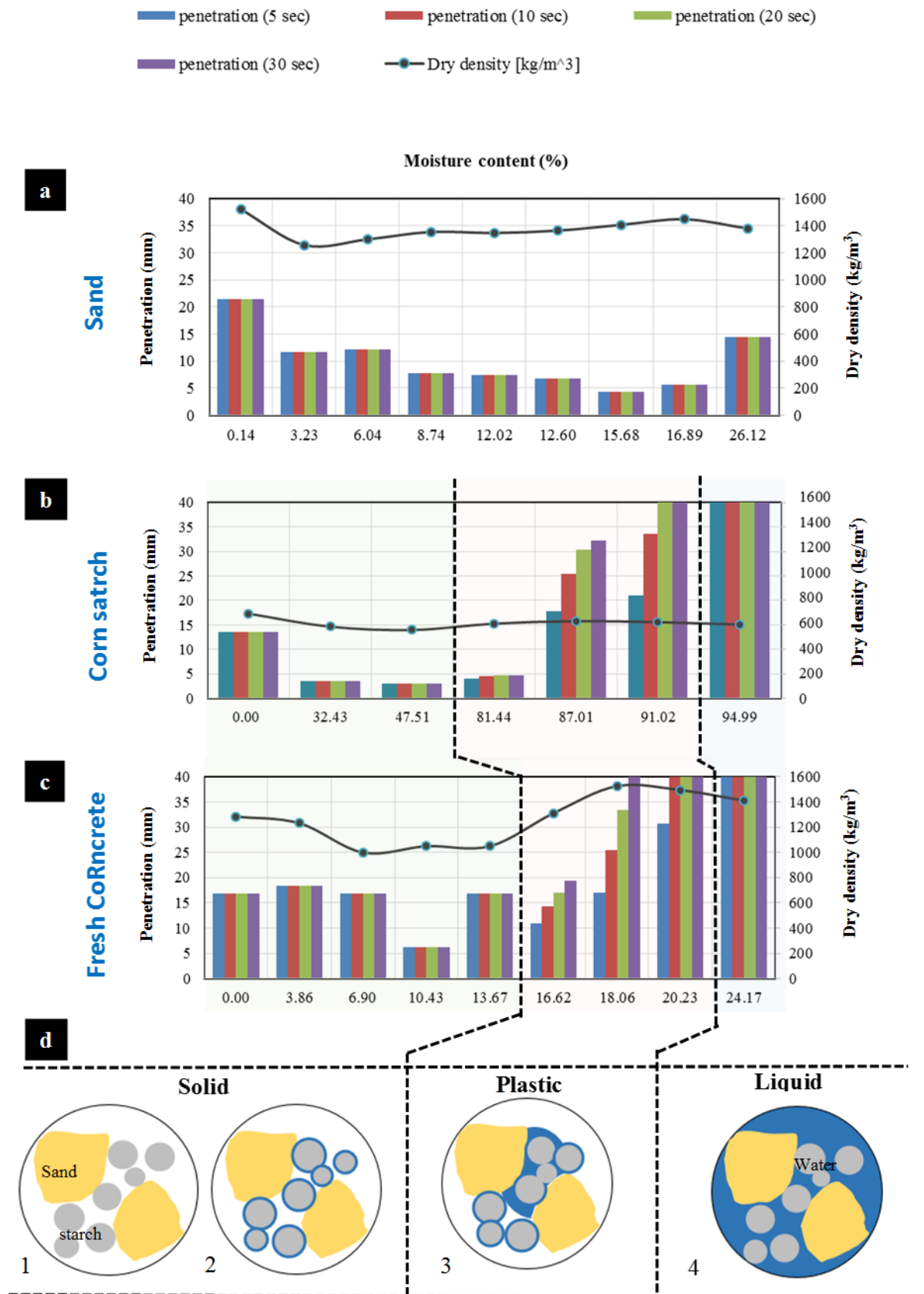
Fig. 3. Cone penetrometer test result of (a) sand, (b) corn starch and (c) fresh CoRncrete and sketch of phase of corn starch in CoRncrete (d).

The dry density measurements in the fallcone tests have limited accuracy due to the small volume of the cup and unquantified compaction energy. In order to obtain a more accurate relationship between density, water content and compaction energy and find the optimum water content corresponding to the maximum dry density of CoRncrete, Proctor tests were performed. In this test the compaction procedure is standardised. The results of the Proctor tests are shown in Fig. 4. At the applied compaction energies, the variation in the dry density of sand was much lower than that of CoRncrete. Compaction curves of sand at both energies have a similar trend. However, in dry state and at full saturation, both curves attain similar dry density. This is due to the lack of capillary forces in dry state allowing the sand to obtain its maximum dry density and the presence of virtually incompressible water in the saturated state, which dampens the compaction energy.

Fresh CoRncrete showed a decrease in dry density with increasing water contents up to 13%. The capillary action of the water and corn starch result in the formation of lumps. The compaction energy is not sufficient to break these lumps, causing the inclusion of air in the sample. With increase in water content beyond 13%, the dry density increased rapidly. At the compaction energy of 22.1 kJ/m³ a maximum dry density of 1589kg/m³ was achieved at 16.6% water content. A maximum dry density of 1547 kg/m³ was achieved at 17.9% when compacted with a higher energy of 51.5 kJ/m³. Similar to the observations during the fallcone tests, a phase change was observed. When the water content increased above the optimum water content the material started to behave like a viscous liquid. With a further increase in the quantity of water from the optimum water content, the dry density decreased and the wet mixture flowed with ease. At a water content of 15% to 20%, the maximum dry density measured for low energy compaction is higher as compared to sand high energy compaction. This is probably due to the stiffening of CoRncrete under higher impact (non-Newtonian behaviour) that may allow inclusion of more air. This might also be caused due to measurement steps that were not close enough to give a detailed curve.
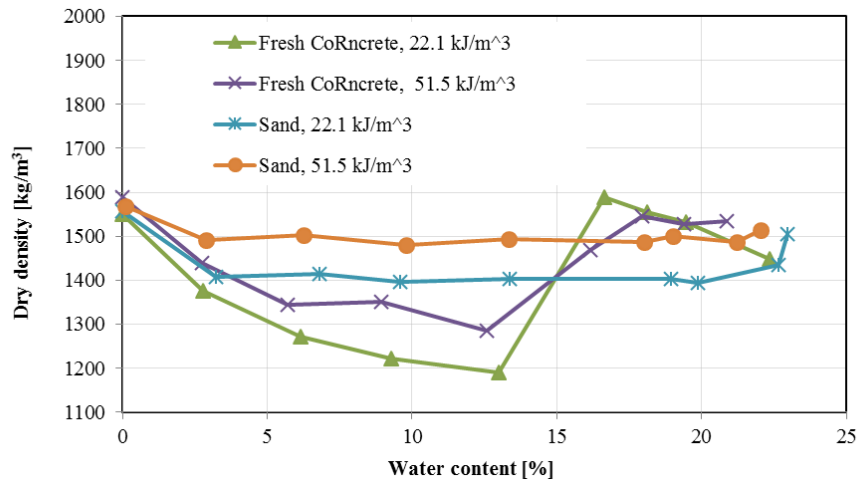

Fig. 4. Results of the Proctor tests.

The optimum water contents measured by the Proctor tests correspond to results of the cone penetrometer test. A water content of 16.66% (Corn starch: Water: Sand:: 1:1:5) was adopted as the optimum water content for fresh CoRncrete for further testing. At this water content, phase transition is expected to occur and it is marked by the maximum dry density of fresh CoRncrete.

3.2 Heat induced transformation of CoRncrete

The heat induced transformation is caused by physical modification of the corn starch, a process called gelatinisation. Gelatinisation of corn starch mainly depends on starch type, amount of water and heating temperature. The gelatinisation process begins at an onset temperature, reaches the maximum activity at the peak temperature and finishes at an end temperature. The gelatinisation temperatures of CoRncrete were determined by DSC test. The onset gelatinisation temperatures of CoRncrete with 15% and 18% water content were measured as 57.3°C and 57.4°C, respectively. The peak temperatures were measured as 65.5°C and 66.1°C, respectively. The end temperatures for both the samples were measured to be around 70°C. This indicates that a minimum temperature of 70°C is required for complete gelatinisation of corn starch, provided no water is lost during the heating process (DSC test samples were heated in an air-tight pan). The gelatinisation temperature of un-modified corn starch was studied by Liu et al. [26] and it was observed that the peak gelatinisation temperature was consistent beyond water to starch weight ratio of 0.5. Assuming no absorption of water by the sand grains, this value corresponds to 8.3% water content in the CoRncrete mixture considered here. The samples prepared in this study all had water contents greater than 8.3%, hence no significant changes in gelatinisation temperatures were expected.

The microstructure of corn starch and CoRncrete was studied using the ESEM. Fig. 5 (a,b) shows corn starch grains of average diameter 15μm. When starch granules are heated in water, they swell gradually. Starch granules swell until a stage when they become fully swollen to their maximum size and they burst. The starch is no longer granular in form but like a thick paste. At this stage, the starch is said to be completely gelatinised. If the swelling is arrested in the plateau prior to maximum swelling or bursting of the granules, the starch is said to be partially gelatinised [30].

The CoRncrete samples imaged under ESEM are shown in Fig. 5(c-l). In presence of low water contents, corn starch was seen to be partially gelatinised (Fig. 5(c,d), while in presence of excess water, the extent of gelatinisation of corn starch was high (Fig. 5.e,f). This indicates that the water content has an effect on gelatinisation of corn starch and it influences the bonding with sand grains, therefore the microstructure of CoRncrete. Fig. 5(g,h) show the microstructure of CoRncrete (water content =16.66%) heated in microwave at 19.8kJ energy. A variation in extent of gelatinisation was observed at different regions which indicate the temperature and water content was unevenly distributed throughout the specimen. A gap between partially gelatinised starch matrix and a sand grain could be seen (Fig. 5(g)) which indicates poor bonding. In completely heated CoRncrete (heated in microwave at 250.8 kJ energy) with a similar water content, a higher degree of gelatinisation was achieved and increased bonding between gelatinised corn starch and sand was observed (Fig. 5.i,j), indicating the effect of heating duration and rate (energy) on the gelatinisation process. A CoRncrete sample (water content=16.66%) heated in oven also showed a low degree of gelatinisation (Fig. 5.k,l). In an oven, the rate of heating is slow and as the top boundary of CoRncrete specimen was open, water could have migrated and evaporated at the surface before the gelatinisation temperature was reached. As a result gelatinisation occurred at a lower water content, resulting in a lower degree of gelatinisation. The different extent of gelatinisation achieved in DSC, microwave and oven specimens indicate the impact of heating equipment, i.e. the heating temperature, heating rate and boundary conditions while heating, on the formation of microstructure of CoRncrete.
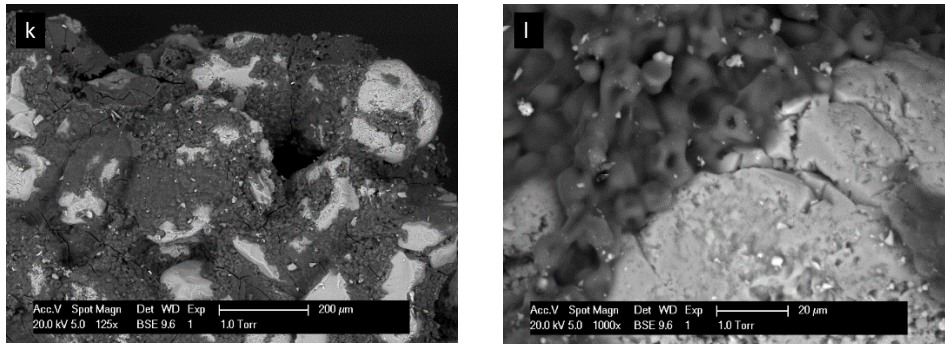
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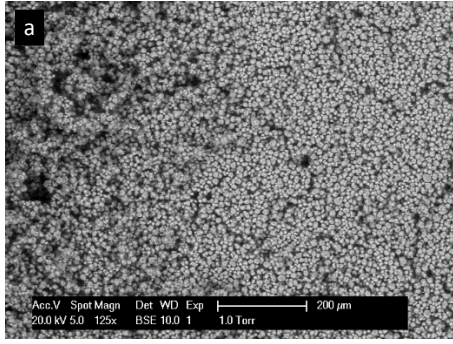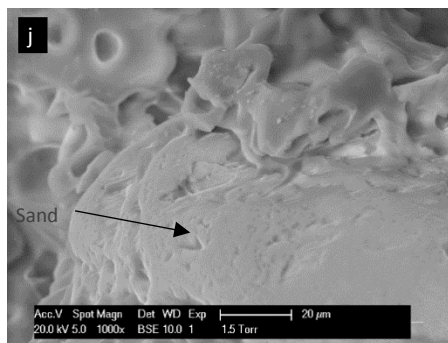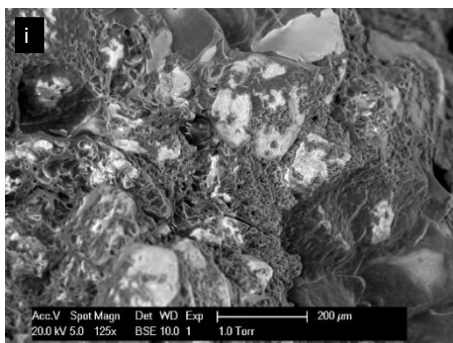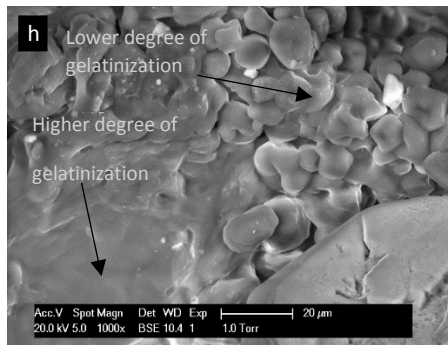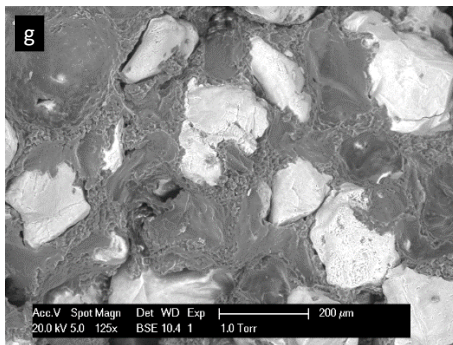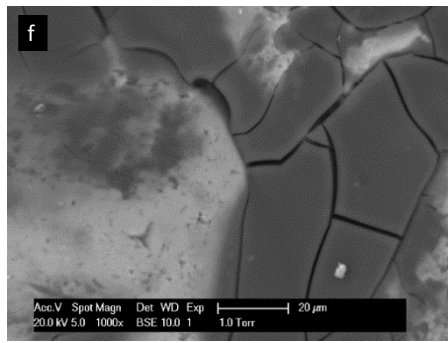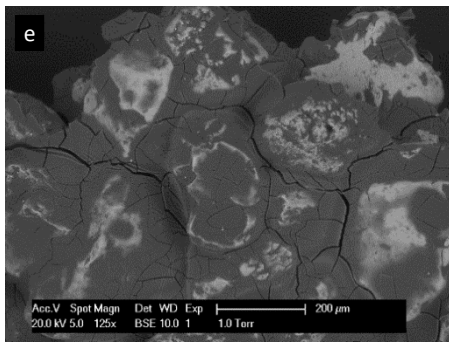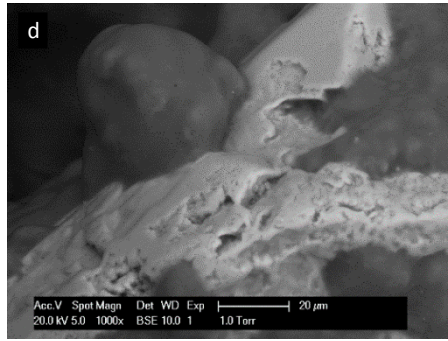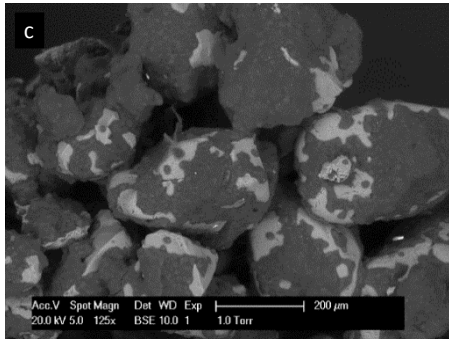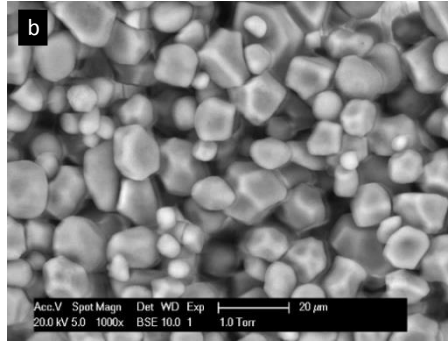
Fig. 5. ESEM image of (a) Corn starch particles (125x), (b) Corn starch particles (1000x), (c) CoRncrete heated in DSC with 15% water content (125x), (d) CoRncrete heated in DSC with 15% water content (1000x), (e) CoRncrete heated in DSC with 18% water content (125x), (f) CoRncrete heated in DSC with 18% water content (1000x), (g) CoRncrete partially heated (19.8 kJ) in microwave with 16.66% water content (125x), (h) CoRncrete partially heated in microwave with 16.66% water content (1000x), (i) CoRncrete heated (250.8 kJ) in microwave with 16.66% water content (125x), (j) CoRncrete heated (250.8 kJ) in microwave with 16.66% water content (1000x), (k) CoRncrete heated in convection oven with 16.66% water content (125x) and (l) CoRncrete heated in convection oven with 16.66% water content (1000x).

3.3 Factors affecting the compressive strength of hardened CoRncrete

3.3.1 Effect of water content

The strength of hardened CoRncrete was observed to be sensitive to the amount of water in the fresh CoRncrete. As shown in Table 2 and Fig. 6, with an increase in water content, the compressive strength increases. However, a decrease in the compressive strength was observed above a certain water content. In all cases a brittle behaviour was seen.

Table 2.
Results of compressive strength test testing on hardened CoRncrete prepared with varying water content. (Shrinkage represented as a positive volume change).

| Heating mode	Water content in fresh CoRncrete [%]	Density of solid CoRncrete [kg/m³]	Volume change [%]	Compressive strength [MPa]
Microwave	10.00	1256	10.77	1.82
Microwave	13.33	1409	16.13	7.28
Microwave	15.00	1552	13.13	26.67
Microwave	16.66	1569	-1.52	21.64
Microwave	18.33	1495	-2.19	15.25
Microwave	20.00	1356	-11.40	-
Oven	10.00	1231	-	-
Oven	13.33	1169	-	-
Oven	15.00	1302	-0.82	1.29
Oven	16.66	1610	1.51	13.70
Oven	18.33	1592	4.96	10.66
Oven	20.00	1522	1.27	9.17
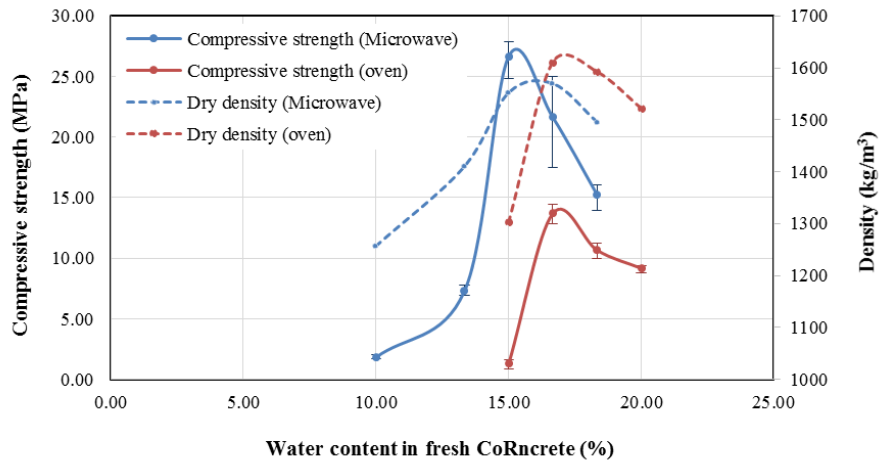
Fig. 6. Compressive strength of hardened CoRncrete with varying water content.

When CoRncrete was heated in a convection oven, very weak specimens were formed at low (10% and 13.33%) water contents (Fig 7(a, b)). With an increase in water content to 15%, a compressive strength of 1.3 MPa was recorded. The compressive strength of CoRncrete increased until 16.66% water content, which is in fact the optimum water content observed for fresh CoRncrete (Fig.4). At optimum water content, the maximum compressive strength of 13.7 MPa was achieved. With an increase in water content to 20%, a reduction in strength was recorded. A positive correlation between compressive strength and the dry density was observed in (Fig.6).

Fig. 7. CoRncrete specimen heated in convection oven with water content (a) 10%, (b) 13.33%, (c) 16.66% and (d) 20%.

In case of microwave heating, the hardened CoRncrete showed a compressive strength of 1.82 MPa at 10% water content. With an increase in water content, the strength increased rapidly and a maximum compressive strength of 26.7MPa was achieved at a water content of 15%. A low strength of 21.6 MPa was recorded at the optimum water content. The trend of reduction in strength continued and a compressive strength of 15.3MPa was observed at 18.3%. The CoRncrete prepared at 20% water content was highly deformed and thus it was unsuitable for compression testing (Fig 8 (d)). A positive correlation between compressive strength and dry density of CoRncrete was also observed for microwave heating, with an exception at optimum water content, i.e. 16.66%. The lower strength at optimum water content could be caused by slight deformation and cracking in the specimens.
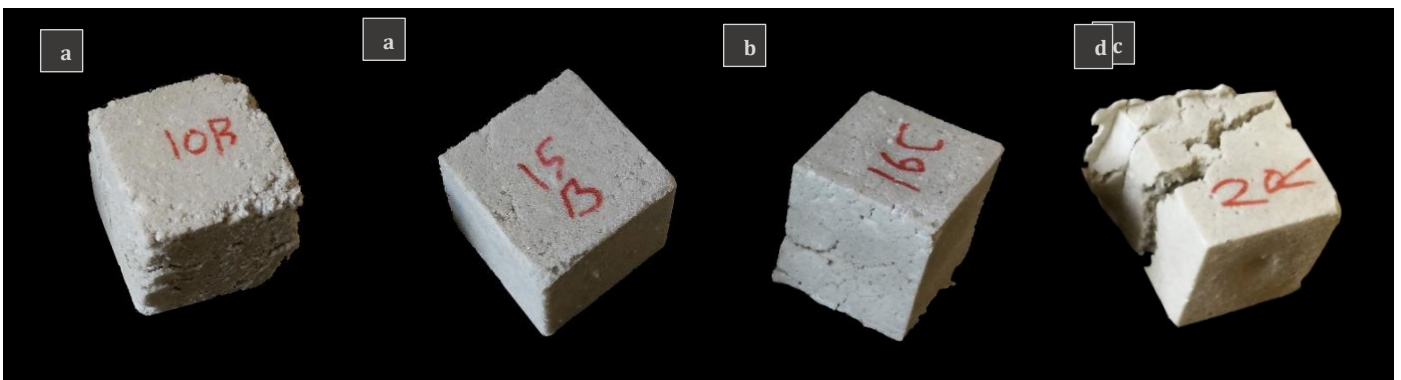

Fig. 8. CoRncrete specimen heated in microwave with water content (a) 10%, (b) 15%, (c) 16.66% and (d) 20%.

The result presented in this section demonstrate the combined effects of water content, density and heating method on the microstructure and therefore, the mechanical performance of CoRncrete. In the previous section on wet CoRncrete it was shown that the density of the CoRncrete mixture is significantly affected by the water content and the highest dry density of the CoRncrete mixture is obtained at the optimum water content of 16.66%. It is evident that the density positively affects the compressive strength, as the dense packing of the sand grains and large number of intergranular contacts increase the number of bonding sites between sand and gelatinised corn starch and require the sample to dilate when it needs to deform as a result of compressive loading. Similar effects of density on the strength of cemented sand were observed by Van Paassen [31].

It can be seen in Fig. 6 that the compressive strength of CoRncrete formed by heating in a microwave was higher than CoRncrete heated in a convection oven. In a microwave, due to the rapid heating and closed boundary condition the temperature of the CoRncrete increased such that the gelatinisation temperature was achieved in short time, while in an oven the low heating rate and open boundary at the top may have caused the water to evaporate before gelatinisation temperature was reached. Thus, in the oven gelatinisation may have occurred at a lower water content, resulting in a lower degree of gelatinisation as compared to microwave heated specimen. The underlying heating mechanism in an oven also results in a temperature gradient within the specimens. The temperature gradient may cause a differential gelatinisation in the specimen, making it heterogeneous as compared to microwave heated samples. Also, the temperature of CoRncrete in microwave is expected to reach up to 250°C as compared to 105°C in the oven, affecting gelatinisation process and subsequent strength development significantly.

Rapid heating also causes the CoRncrete specimens to deform. According to Ni et al. [32], in a wet and quite impermeable material, the combination of high heating rates and low permeability is likely to generate high internal pressures. At low water contents the specimens experienced shrinkage due to increased capillary suction pressure [33]. The shrinkage results in a denser packing thus affecting the compressive strength of specimens heated in microwave positively. Shrinkage up to 16% and 13% was measured in CoRncrete specimens heated in microwave at 13.3% and 15% water content respectively. The strength of CoRncrete at lower water content than optimum is dependent on the shrinkage (which results in the increase of density and sand-starch interaction) and extent of gelatinisation (which is dependent on water content). At very low water content, the amount of water is insufficient for complete gelatinisation resulting in insufficient bonding of sand-starch matrix. At high water contents, the high internal pressures which occur at high heating rates, may have caused strong filtration flows, resulting in the cracks as observed in CoRncrete shown in Fig. 8 (c,d). This may have caused the reduced strength at the optimum water content of 16.7% and above. Higher strengths were expected due to high degree of gelatinisation as seen in ESEM image in Fig.5 (i,j). However, lower strengths were observed due to the formation of cracks as a result of filtration flow. With a further increase in water content, deformation and cracking in the specimen increases, resulting in a higher deviation of test results and therefore, decrease in strength.

In both heating methods, the CoRncrete with higher densities performed well in compression. Sand grains are expected to be closer to each other in a denser CoRncrete, thus the interfacial area of sand-starch matrix would be higher. As seen in Fig.6, a higher force is required to fail the denser specimens which suggest that the interface is not the weakest link in specimen. Also, a larger number of micro cracks (caused due to shrinkage at microscale) are expected in a low density CoRncrete as compared to the high density CoRncrete due to increased average distance between sand grains. The larger number of micro cracks are expected to localize at a lower force. This indicates that specimens with increased average distance (low density) may require less force to cause localization of cracks which subsequently result in the failure of specimens.

3.3.2 Effect of sand grain size

The size of the sand grains have a significant influence on the compressive strength of CoRncrete. It can be seen in Fig. 9 that irrespective of the source of heating, with an increase in sand grain size, compressive strength decreases. The water content of 16.66%, i.e. the specimens with highest compressive strength (for both microwave and convection oven), was adopted to study the effect of sand grain size. The strength of oven heated CoRncrete reduced from 10.7MPa to 2.64MPa with the use of coarser sand grains (1.0-2.0mm). While the strength of CoRncrete heated in a microwave (15% water content) decreased from 26.67 MPa to 6.32 MPa. It was observed that the strength of CoRncrete with 0.5-1.0mm sand grains was higher than CoRncrete with 0.25-0.5mm sand grains. This was probably due to burning of corn starch, which was observed for the specimen with 0.25-0.5mm sand grains. In order to prevent the influence of excessive heating on test results, it was decided to repeat the test with a lower heating energy of 217.8kJ (1.5 min thaw+3 min high power). The compressive strength results of these specimens (red bars in Fig.9) followed the trend of decreasing strength with increasing sand grain size. This also indicated that the ideal heating scheme for each type of CoRncrete could be different. It can also be seen in Fig. 9 that, with an increase in the size of sand grain, the shrinkage of CoRncrete reduces (shrinkage represented as positive volume change).
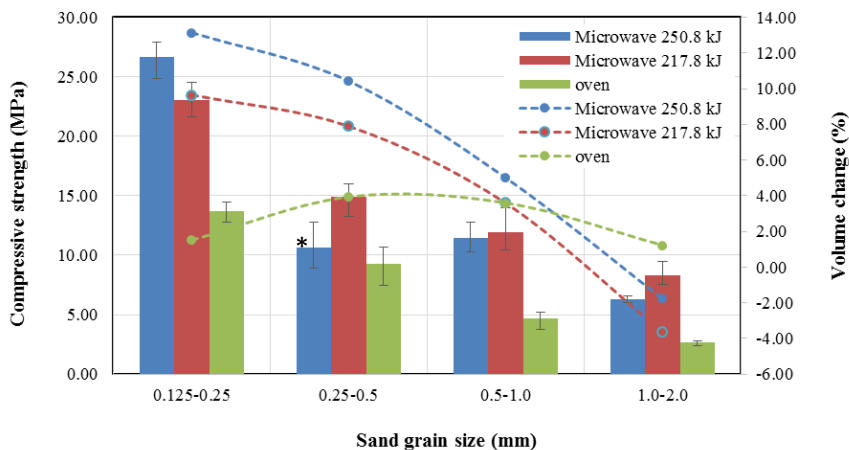
Fig. 9. Variation of compressive strength of hardened CoRncrete with increasing sand grain size. The bar and the dotted line represents the compressive strength and volume change respectively. (*) samples were observed to burn.

The observed effect of grain size on the strength of hardened CoRncrete may be explained as follows: With an increase in grain size, the specific surface area of the sand grains and the amount of intergranular contacts (per unit volume) decrease, resulting in the reduction of sand-starch interfacial area. Thus, a lower force is expected to cause the failure of specimen with lower sand-starch interfacial area. Also, with an increase in the size of sand grain, the average distance between sand grains is expected to increase. As postulated in Section 3.3.1, localization of micro cracks might be favourable when the distance between grains is more. Hence, the CoRncrete with larger grain size result in lower strength. The two postulates put forward are speculation and further testing is required to comment on the observed behaviour.

3.3.3 Effect of heating duration in microwave

The heating duration or heating energy has a pronounced effect of gelatinisation process and the bonding of sand-starch matrix. The effect of heating duration on CoRncrete specimen prepared with 15% water content is shown in Fig. 10. The specimen heated at 85.8 kJ (1.5min in thaw mode) was still soft. With an increase in heating energy to 151.8 kJ, the gelatinisation process advanced and resulted in a rapid increase of compressive strength. A significant reduction in moisture is also observed at this energy. Beyond this heating energy, the variation in compressive strength and moisture content in hardened CoRncrete is low. The maximum compressive strength of 26.66 MPa was achieved by heating CoRncrete at 250.8 kJ energy. With further heating, the removal of moisture becomes difficult as it is tightly held by gelatinised corn starch matrix. This may cause a rise in temperature beyond 290°C and corn starch starts burning (290°C is the burning temperature of corn starch which was measured by Thermogravimetric analysis, TGA). The burning of corn starch may affect the strength of CoRncrete negatively. Burning marks were visible on the specimens. The quantity of water, size of sand grains, type of mould and boundary conditions (while heating) is expected to affect the heating of CoRncrete. The heating and gain in strength was also strongly dependent on the frequency, energy and size of microwave oven.
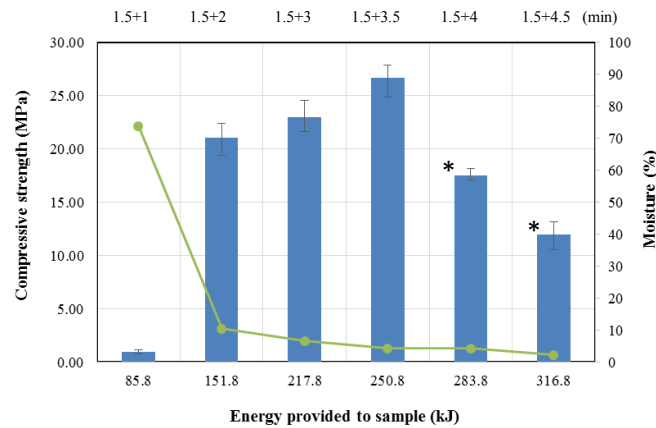

Fig. 10. Effect of heating duration in microwave on the compressive strength and moisture content of CoRncrete. (*) samples were observed to burn. The bar and the line represents the compressive strength and moisture content respectively.

It is important to note that apart from the factors discussed in the present study, the shape and size of CoRncrete is expected to have a significant effect on the strength of CoRncrete.

3.4 Degradation of CoRncrete

The use of corn starch makes CoRncrete a biodegradable material. This may on the one hand be ecologically attractive but impacts the durability of CoRncrete in a wet environment negatively. Under water submerged conditions (20°C), hardened CoRncrete specimens showed partial to complete degradation within a day. CoRncrete with a lower degree of gelatinisation (heated in a microwave with 15% water content and heated in an oven with 16.66% water content) showed complete degradation in a day. Specimens with higher extent of gelatinisation (heated in microwave with 16.66% water content) degraded more slowly resulting in 33% and 65% reduction in surface hardness in 1 and 7 days respectively in water submerged environment (measured by Equotip hardness non-destructive testing). A video on degradation of CoRncrete in wet environment is available on YouTube [34]. The degradation of CoRncrete is significantly affected by the extent of gelatinisation.

3.5 Sustainability analysis

Mohanty et al. [35] has defined a sustainable bio product as a product derived from renewable resources having recyclable capabilities and triggered bio-degradability with commercial viability and environmental acceptability. CoRncrete is derived from renewable maize crop and it has potential to be recycled. The environmental acceptability or performance of CoRncrete is important to analyse in order to use it as a green alternative to traditional building materials like fired clay brick and Portland cement concrete.

An elementary environmental performance of CoRncrete was performed using Life cycle assessment (LCA) based on methodology as prescribed in ISO 14040:2006 [36]. The goals of the LCA analysis were to compare the environmental effect of CoRncrete with traditional building materials like Portland cement concrete and fired clay bricks and to identify the life cycle stage of CoRncrete that is contributing most to any environmental impact. For the analysis, $1m^3$ of material, of strength 25MPa in the application as a structural block for indoor use with an expected life of 50 years was compared. The scope or system boundary for LCA was restricted from processing of raw material ('cradle') to manufacturing of ingredients for building material ('gate'). This restricted scope is due to unavailability of recyclability data. The quantity of ingredients for the manufacturing of materials are shown in Table 3. The LCA study was carried out based on the product life cycle inventory (LCI) database from Eco-costs V3.3 [37]. A total of 12 environmental categories were evaluated. The environmental categories are expressed as 'cost to environment' in Euros per m^3 of material.

Table 3.
Quantity of various ingredient in CoRncrete, Portland cement concrete and fired clay brick

Ingredients	Quantity of material(kg/m³)*		
	CoRncrete	Concrete	Brick
Corn starch	255	-	-
Cement	-	298	-
Water	230	185	-
Coarse aggregate	-	992	-
Fine aggregate	1277	882	-
Bulk density of fresh material	1763	2357	N.A
Density of hardened material	1552	2357	1920
Air %	N.A	2	N.A

The Life cycle impact assessment of the materials is shown in Fig. 11. The total eco-cost of CoRncrete, Portland cement concrete and fired clay brick is 90.7, 57.9 and 84.7 Euros/m³ respectively. Corn starch is responsible for 95% of the total eco-cost of CoRncrete. The major environmental category responsible for higher eco-cost of CoRncrete is human health and eco-toxicity. CoRncrete has 5 times higher impact on human health and 3 times higher impact on eco-toxicity as compared to concrete. Acidification potential, human toxicity and fine dust are the three main environmental categories impacting human health and eco-toxicity. Acidification potential of CoRncrete is 2-3 times that of concrete and brick. Whereas, human toxicity due to the production of CoRncrete is 13 times higher than that of concrete. The carbon footprint of CoRncrete is lower than bricks and comparable to concrete.

The higher eco-cost in human health and eco-toxicity categories is due to use of chemical fertilizers, pesticides, energy and water during crop growth stage. This assertion is supported by the study of Vercalsteren et al. [38] that claims that crop growing stage makes up the largest part of environmental impact for starch based products. Their study also suggest that a starch product with longer life may also result in negative carbon footprint. Kim and Dale [39] studied the LCA of corn starch-based ethanol. According to them, the use of fertilizer could result in Nitrogen loss from soil and might contribute to greenhouse gas emission, acidification, eutrophication and photochemical smog. Higher greenhouse emission and acidification are also observed in LCA of CoRncrete. Another possibility which may have resulted in higher eco-cost in acidification and human toxicity environmental category is the release of SO_2 during the production of corn starch. To make any strong conclusion on sustainability of CoRncrete, a detailed analysis considering the full life cycle of materials should be adopted. The present analysis over the partial life cycle of the material shows a higher environment impact of CoRncrete, which may not fully represent reality due to eco-friendly properties such as recyclability and biodegradability of CoRncrete or use of biomass to produce starch.
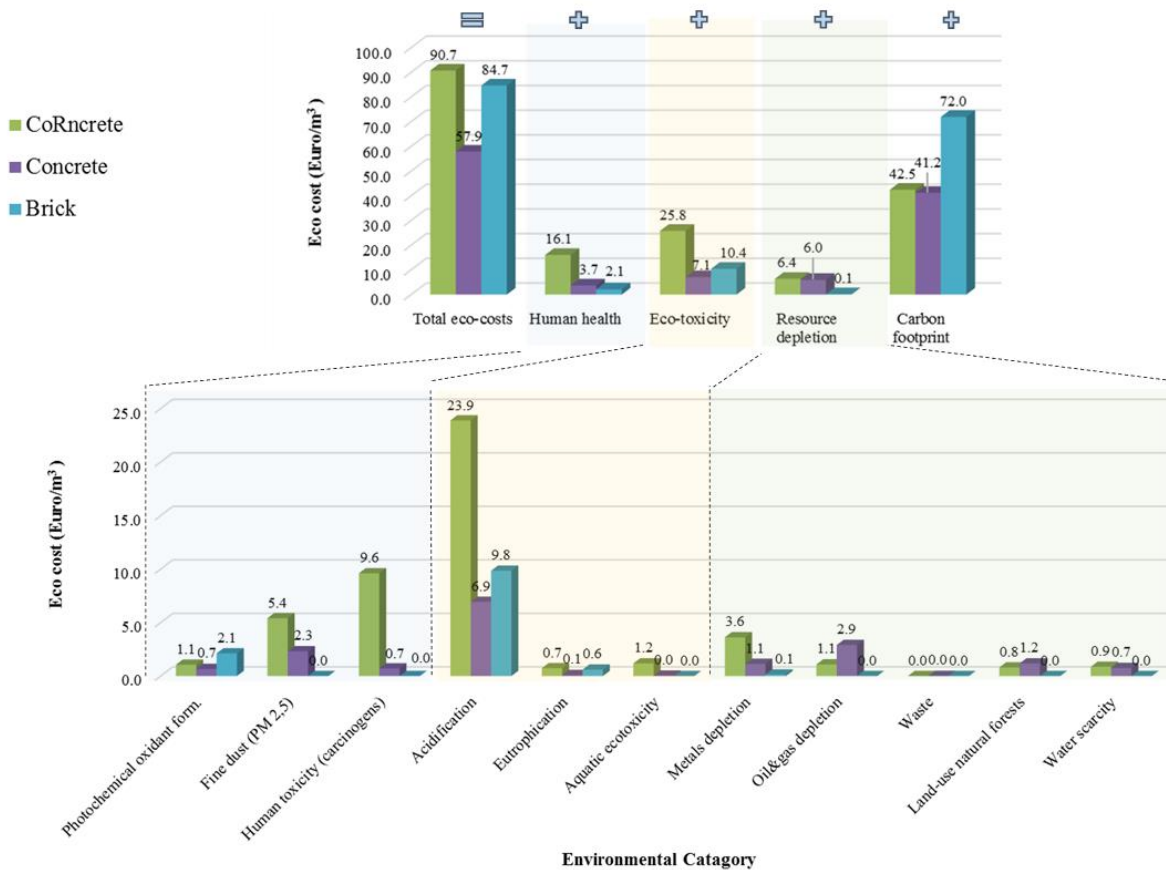
Fig. 11. Life cycle impact assessment of CoRncrete, Portland cement concrete and fired clay brick.

3.6 Application of CoRncrete and its limitation

CoRncrete is a bio-based material that achieves its final strength in few minutes as compared to several days required to manufacture traditional building materials. Moreover, CoRncrete (1552 kg/m³) is 19% and 34% lighter than red clay brick (1920kg/m³) and Portland cement concrete (2357 kg/m³), respectively. These advantages, combined with its derivation from renewable sources, make it an interesting material. CoRncrete can be used as a structural block, similar to the brick, in dry environments which are available in arid regions and inside a building. These blocks would typically require a mortar to join them, which could be reduced via use of an interlocking shape. Alternatively, fresh CoRncrete could be used as a mortar, with appropriate in-situ heating. The gain in strength upon heating at a relatively low temperature and the flow properties of CoRncrete also makes it an interesting material for potential 3D printing of buildings. In-situ heating of CoRncrete is one of the main challenges for its upscaling. The use of solar powered heating equipment can be considered as a sustainable heating alternative.

The degradability of CoRncrete affects its application both positively and negatively. Although, it cannot be used on the exterior of buildings, it may find applications in temporary structures. CoRncrete is expected to degrade very slowly in non-submerged environments. Use of a hydrophobic additive or coating could be a viable option to improve the durability. The use of corn starch also affects the environmental performance of CoRncrete. In recent years, the use of corn starch in industrial applications has raised debate over competition with food industry. The use of corn starch in ethanol production has resulted in an increase of corn starch price up to 80% [40]. The environmental performance of CoRncrete assessed in this paper, over its partial life-cycle, proves it to have a higher eco-cost than traditional building material. Utilization of biomass or feedstock from maize crops in the production of starch can be an alternative to manufacture CoRncrete with a low environmental impact.

The properties of CoRncrete could be modified with the use of chemical additives. These additives can influence the gelatinisation process which may result in stronger and more durable CoRncrete. The heat induced transformation is not only limited to corn starch, therefore other starches such as potato starch can be utilised to form a hardened material.

4. Conclusions

This article introduces a bio-based construction material, CoRncrete, which is formed by heating a mixture of sand, water and corn starch. Heating of corn starch in the presence of water results in the formation of a gel that hardens and binds with sand grains. The transformation of CoRncrete from a semi-solid to a hardened material was measured to occur at about 66°C. The wet (unhardened) CoRncrete appeared to be self-compacting and obtained a maximum density at the optimum water content of approximately 16.6%, which depends on the applied compaction energy and corresponds to the water content at which corn starch changes phase from solid particles (with some adsorbed water) to particles in suspension of water. A higher compressive strength was also recorded at this optimum water content. Compressive strengths of up to 26.67 MPa was achieved when the material was heated by a microwave,

whereas it was limited to 13.70 MPa using an oven. The test results indicated a positive correlation between compressive strength and the density of CoRncrete. The strength of CoRncrete has been shown to be highly sensitive to water content and is significantly affected by varying the size of sand grains and the heating method and duration.

Durability of CoRncrete seems to be limited under wet conditions as the CoRncrete specimens showed complete to partial degradation within a day when submerged in water. The life cycle assessment of CoRncrete over its partial life cycle (cradle to gate) indicate that the CoRncrete has a higher environmental impact as compared to red clay brick and Portland cement concrete. The higher eco-cost of CoRncrete is mainly due to the use of fertilizer that results in higher eco-toxicity and affect human health adversely. If this aspects can be eliminated, CoRncrete may offer potential reductions in environmental impact.

Based on these results it can be concluded that CoRncrete is an attractive building material due to its light weight, rapid gain in strength, good compressive strength, biodegradability and its derivation from renewable sources. However, factors such as durability and sustainability provide challenges for commercial applications.

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