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Synthesis, characterization and applications of nano/micro carbonaceous inerts: A review

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Abstract

In recent years, a scientific shift has been observed towards the use of carbon based nano materials in different composites to enhance their mechanical and electrical properties. However, carbonaceous nano/micro inert particles synthesized through pyrolysis of agricultural and industrial wastes offer a very cost effective alternate to the commercially available carbon based materials such as carbon fibres, carbon nanotubes, graphene and graphene oxide. A comprehensive survey of reported data on the synthesis of carbon particles is presented in this article. The utilization of synthesized carbon particles as reinforcing material has also been explored together with an attempt of proposing future novel applications of synthesized carbon particles in cement based systems. In this paper, meticulous efforts have been made to overview the potential beneficial effects of synthesized carbon particles intrusions to cementitious systems for modifying/improving their mechanical characteristics.

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1. Introduction

There has been a growing trend in the utilization of carbon based nano/micro materials in variety of composites to enhance their physical, mechanical and electrical properties. These nano/micro additions (Gogotsi & Presser, 2013)

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includes carbon fibres (CF), single and multiwall wall carbon nanotubes (SWCNT and MWCNT) (De Volder, Tawfick, Baughman, & Hart, 2013; Gojny, Wichmann, Köpke, Fiedler, & Schulte, 2004; Hiremath, Mays, & Bhat, 2017), graphene oxide (GO) (Gong et al., 2014; Lu, Lu, Li, & Leung, 2016; Zhu et al., 2010), graphene nano platelets and (GNP)(Chatterjee, Nüesch, & Chu, 2011) and the literature indicates their capability of imparting high strength, ductility, dimensional stability, electromagnetic interference shielding, economy etc. to the resulting composites.

In construction industry, cement and concrete composites are the most utilized materials around the globe (T. R. Naik, 2008). The production of cement is the most energy intensive process producing approximately 7.0% of the total anthropogenic production of carbon di oxide (CO_2) in the atmosphere. CO_2 is a major greenhouse gas responsible for the global warming and destruction of the environment (Oh, Noguchi, Kitagaki, & Park, 2014). Therefore, it is highly desirous to enhance the mechanical strength and the durability of the cementitious composites to reduce the carbon footprints of the construction industry. An effective way to achieve sustainability and environmental friendliness is to incorporate waste materials in the production of cementitious composites.

It has been reported in the literature that the use of industrial waste materials such as fly ash, silica fume, blast furnace slag, lime stone powder, marble powder, glass powder etc. improve economy, mechanical characteristics and durability. Similarly, organic and agricultural wastes are also being produced in enormous quantities throughout the world which may be employed to employed effectively for various purposes (Polprasert, 1989). Although there are several ways to convert agricultural/organic waste to bio-char and biofuel (i.e. gasification, fermentation, combustion, extraction, liquefaction, digestion, enzymatic conversion and chemical conversion), pyrolysis is the most effective and recognized technique for converting both soft and hard organic waste in to useful carbonaceous inert material (Mettler, Vlachos, & Dauenhauer, 2012; S. N. Naik, Goud, Rout, & Dalai, 2010).

In the present research, it is aimed to study the synthesis methodologies of carbonaceous particles from the agricultural/ organic wastes and the characterization techniques employed to study these particles. The utilization of synthesized carbonaceous particles in various applications has also been explored together with an attempt to propose future novel applications of these particles.

2. Synthesis of carbonaceous inerts

Bio-char is a carbonaceous material in solid form that is yielded when an organic mass is thermo-chemically decomposed at elevated temperature usually ranging from 450 to 550 °C in an oxygen-depleted atmosphere. This process of controlled thermochemical decomposition of organic mass is called pyrolysis (Hammond, Shackley, Sohi, & Brownsort, 2011; Woolf, Amonette, Street-Perrott, Lehmann, & Joseph, 2010). Based upon the heating rate, the pyrolysis technique may be referred as slow, medium or fast pyrolysis. In slow pyrolysis, a low heating ramp e.g. 2 to 5 °C/min is employed with relatively longer residence of the organic material. Where as in fast pyrolysis heating ramp may be about 100°C/min. The heating ramp and the residence time strongly effect the carbonaceous inerts yield and their characteristics. The influence of pyrolysis temperature and residence time is briefly discussed in following sections.

2.1. Materials used for the synthesis of carbonaceous inerts

The pyrolysis technique can be employed to synthesize carbonaceous inert particles from approximately all the organic materials. Several researchers worked on the pyrolysis of various agricultural, municipal and industrial wastes. Demirbas et. al. studied the pyrolysis of beech trunk bark for different temperatures and at different heating ramps (Demirbas, 2004a). In another study, Demirbas et. al. used olive husk, corncob and tea waste for pyrolysis to get bio-char and bio oil (Demirbas, 2004b). Ucar et. al. prepared Bio-char and bio-oil from pyrolysis of rapeseed oil cake (Ucar & Ozkan, 2008). Ucar further performed the pyrolysis of pomegranate seeds which is a by-product of fruit-juice industry (Ucar & Karagöz, 2009). Bio-char from soybean oil cake was prepared via pyrolysis by Tay et. al. (Tay, Ucar, & Karagöz, 2009). Woody-wastes was used by McHenry et. al. to produce bio-char through pyrolysis (McHenry, 2009). Mullen et. al. utilized corn cobs and corn stover (leaves, stalk and husk) as biomass and performed pyrolysis to convert these into bio-char and bio-oil (Mullen et al., 2010).

Liu et. al. prepared bio-char from the pyrolysis of corncobs and rice husk (W.-J. Liu, Zeng, Jiang, & Zhang, 2011) Muradov et. al. used an aquatic bio mass, Lemna minor to get bio-char through pyrolysis (Muradov, Fidalgo, Gujar, Garceau, & Ali, 2012). Pyrolysis of waste from the palm oil industry, palm shell, mesocarp fiber and empty fruit bunches were performed by Abnisa et. al. to get bio-oils and bio-chars from these biomass (Abnisa, Arami-Niya, Daud, & Sahu, 2013). Mohan et. al. produced bio-char from the pyrolysis of oak wood and oak bar (Mohan, Kumar, Sarswat, Alexandre-Franco, & Pittman Jr, 2014). Bio-chars were produced from fast pyrolysis of Canadian waste biomass. These waste include wheat straw and flax straw (agricultural waste), sawdust (forest residue) and poultry litter (animal manure) (Azargohar, Nanda, Kozinski, Dalai, & Sutarto, 2014). Bio-char and bio-oil has also been prepared from animal fatty wastes (lamb, poultry and swine) via pyrolysis (Hassen-Trabelsi, Kraiem, Naoui, & Belayouni, 2014). Zhao et. al. used Switchgrass and converted it into bio-fuel via pyrolysis.

Leng et. al. used rice husk to produce bio char through thermochemical liquefaction of bio mass in an autoclave reactor (Leng, Yuan, Zeng, et al., 2015). Leng et. al. further produced bio-char from thermochemical liquefaction of sewage sludge in an autoclave reactor (Leng, Yuan, Huang, et al., 2015). Alkali lignin (by-product of paper industry) was utilized by Wang et. al. as a biomass for pyrolysis to synthesize bio-char (Wang, Ren, Chang, Cai, & Shi, 2015). Ferro et. al. performed the controlled pyrolysis of coconut coir to get solid carbonaceous inerts (G. Ferro, Tulliani, Lopez, & Jagdale, 2015). Hemp et. al. herds that is an agricultural waste is also employed by Ferro to get carbonized inerts (G. A. Ferro, Ahmad, Khushnood, Restuccia, & Tulliani, 2014). Khushnood et. al. consumed peanut shells and hazel nuts shells (agricultural waste) for pyrolysis to get bio-char (Khushnood et al., 2015). Ahmad et. al. used bamboo stems and performed pyrolysis to get carbonaceous nano materials (Ahmad, Khushnood, Jagdale, Tulliani, & Ferro, 2015). Restuccia et. al. obtained bio-char from pyrolysis of hazelnut shells and coffee powder (Restuccia & Ferro, 2016). Akhtar et. al. has performed pyrolysis on poultry litter, rice husk and pulp and paper mill sludge to produce carbonaceous materials (Akhtar & Sarmah, 2018). Recently Gupta et. al. has performed pyrolysis of mixed wood saw dust at 300 °C to get bio-char (Gupta, Kua, & Dai Pang, 2018a; Gupta, Kua, & Low, 2018).

2.2. Methods of Synthesis of carbonaceous inerts

Slow pyrolysis of pomegranate seeds, a by-product of fruit-juice industry,may produce carbon rich bio-char with high bulk density (Ucar & Karagöz, 2009). Fast pyrolysis of Corncobs and corn stover (leaves, stalk and husk) yielded 60% bio-oil, and around 17-19% carbon rich bio-char with few traces of other minerals (Mullen et al., 2010). The bio-char produced by the pyrolysis depends upon the prior treatment of the biomass for example fast pyrolysis of raw, alkali and acid treated biomass indicated that alkali treated biomass was more porous and possessed more surface area than the acid treated and raw biomass (P. Liu et al., 2012). Fast pyrolysis was performed on oak wood and oak bar. Bio-chars obtained were found as potential green absorbents, Pb^{2+} and Cd^{2+} can be effectively removed from contaminated water using them (Mohan et al., 2014). Bio-chars were produced from fast pyrolysis of wheat straw and flax straw (agricultural waste), sawdust (forest residue) and poultry litter (animal manure). Physiochemical changes of bio-char with 400-550 °C pyrolysis temperature were analyzed. Aliphatic/aromatic carbon content increased with increase in pyrolysis temperature for all wastes except poultry litter. In comparison of other inorganic elements large alkaline were found which shows great agricultural potential of these bio-chars. Maximum salinity was obtained at 400 °C for all bio-chars (Azargohar et al., 2014).

Catalytic pyrolysis of alkali lignin (by-product of paper industry) was performed. $CaCl_2$, $FeCl_3$ and KCl were used as additives. Alkali lignin was soaked in water solution of these additives and then dried to remove the water from it. It was found that addition of KCl increased the bio-char production. $CaCl_2$ and $FeCl_3$ addition increased bio-oil yield. $FeCl_3$ addition improved both bio-oil and bio-char quality (Wang et al., 2015). High absorption capacity bio-chars were prepared via pyrolysis of corncobs and rice husk. Keeping temperature constant it was analyzed that retention time was the key factor influencing the absorption capacity, surface area and functional group content of bio-chars (W.-J. Liu et al., 2011).

Bio-char was produced from rice husk via thermochemical liquefaction in an autoclave reactor. Liquefaction of biomass was performed with water, ethanol or water/ethanol as a solvent. Bio-char produced with liquefaction from water/ethanol or water as solvent was rich in phenolic group; and bio-char with ethanol as solvent was rich in lactonic and carboxylic group. Ethanol bio-char rich in carboxylic group proved to be effective for removing malachite green from water. Ethanol solvent also gave more bio-oil and bio-char yield than other two solvents (Leng, Yuan, Zeng, et al., 2015). Thermochemical liquefaction method was used to produce bio-char from sewage sludge in an autoclave reactor. Ethanol and methanol were used as solvent at 260-380 ^{0}C. Lesser quantity of bio-char was produced with low surface area. However this bio-char was rich in oxygen-containing functional groups (Leng, Yuan, Huang, et al., 2015).

Carbon micro/nano particles were prepared via chemical vapor deposition of polyethylene beads and controlled pyrolysis of coconut coir. when added up to 0.08% by weight of cement in cement composites, both type of carbon based micro/nano particles gave improved compressive strength and toughness. (G. Ferro et al., 2015)

2.3. Effect of pyrolysis temperature on bio-char characteristics

Demirbas. et. al. investigated the effects of temperature of pyrolysis on the characteristics of both bio-char and pyro-oil. Yield of pyro-oil was increased with pyrolysis temperature but bio-char yield was reduced with increased pyrolysis temperature. However bio-char obtained at high pyrolysis temperature was rich in carbon and more pure. (Demirbas, 2004a). Lower the pyrolysis temperature, the higher the carbon recovery of the biomass in form of bio-char (Lehmann, Gaunt, & Rondon, 2006). Ucar studied the effect of pyrolysis temperature on the composition of bio-char obtained from the pyrolysis of rapeseed oil cake. Pyrolysis was done on temperature of 400, 450, 500, 700, and 900 °C. Yield of bio-char was decreased from 38.4% to 30% when temperature was increased from 400 to 900 °C (Ucar & Ozkan, 2008). Effect of temperature and chemical reagents on bio-char yield and porosity was investigated in this study. Bio-char from soybean oil cake was prepared via pyrolysis at 600 and 800 °C and by chemical activation of KOH and K_2CO_3. Bio-char prepared by chemical activation of K_2CO_3 was more porous and gave more yield than KOH. Ash and sulphur content was also less in this activated carbon. It gave maximum surface area at 800 °C which was comparable with commercially available bio-char (Tay et al., 2009). Effect of pyrolysis temperature and chemical activation on bio-char yield and quality of pomegranate seeds was investigated in this study. $ZnCl_2$ as chemical reagent with different impregnation ratios at different temperatures was analyzed. Chemical activation improved the bio-char yield for all temperatures. Highest surface area was obtained at 600 °C with impregnation ratio of 2.0 which was comparable to the commercially available activated carbon. This activated carbon can be used to clean industrial wastewater and waste gases (Uçar, Erdem, Tay, & Karagöz, 2009). Effect of temperature on bio-char yield for the pyrolysis of animal fatty wastes (lamb, poultry and swine) was studied and it was found that pyrolysis temperature of 400 °C gave the maximum yield of bio-char and temperature of 550 °C yielded the minimum amount of bio-char. This bio-char was not considered a good energy source due to high ash content and low carbon content (Hassen-Trabelsi et al., 2014).

2.4. Effect of heat ramp on bio-char characteristics

For heating rate, authors working on different type of wastes reported different trends. Inguanzo et al. (2002), studied the pyrolysis of sewage sludge and established that the higher the pyrolysis heating rate, lesser will be the production of bio-char (Inguanzo, Domınguez, Menéndez, Blanco, & Pis, 2002).

Demirbas. et. al. also investigated the effects of heating rate of pyrolysis on the characteristics of both bio-char and pyro-oil. He concluded that high heating ramp yielded more pyro-oil but quality of pyro-oil obtained at lower heating ramp was superior. But bio-char yield was reduced with increased heating ramp (Demirbas, 2004a). Moreover, Mohan et al. (2006), reported for woody materials that the increase of the heating rate reduced the yield of bio-char as it induced an enhancement of bio-oil production (Mohan, Pittman, & Steele, 2006).

Bio-char, bio-oil and syngas were prepared from animal fatty wastes (lamb, poultry and swine) via pyrolysis. Effect of heating ramp on bio-char, bio-oil and syngas yield was studied and it was found that heating ramp of 15 °C/min gave the maximum yield of bio-char (Hassen-Trabelsi et al., 2014).

2.5. Effect of raw material on bio-char characteristics

Demirbas et. al. also studied the effect of raw material size, and lignin and inorganic content, on the bio-char quality and reactivity. Slow pyrolysis of olive husk, corncob and tea waste was performed for high pyrolysis temperature (950-1250 K). He found that bio-char yielded less for small size particles. Bio-char yield was more for high lignin in olive husk than corncob, and the former was more reactive in gasification (Demirbas, 2004b). Pyrolysis of waste from the palm oil industry, palm shell, mesocarp fiber and empty fruit bunches were done to get bio-oils and bio-chars from these biomass. Palm oil waste yielded less bio-char than bio-oils, and more than 40% of the waste can be converted into bio-oil via pyrolysis. Lignin, hemicelluloses and cellulose are main components of biomass, and their presences have great influence on bio-char yield. Palm shell gave highest yield of bio-char due to the highest content of lignin which is very difficult to decompose (Abnisa, Arami-Niya, Daud, & Sahu, 2013).

Pyrolysis of oil palm tree residues (palm leaf, palm leaf rib, frond and trunk) was performed for a reaction time of 60mins, at a temperature of 500 °C, and with nitrogen flow rate of 2L/min. Bio-char and bio-oil yield was different for different residues depending upon lignin, cellulose, hemicellulose, ash and fixed carbon in the sample. Bio-char energy density was higher than bio-oil yielded in the process. Palm leaf sample gave best energy density bio-char and frond sample gave best energy density bio-oil (Abnisa, Arami-Niya, Daud, Sahu, & Noor, 2013). Efforts were made to convert switchgrass bio-material into bio-fuel via pyrolysis. The bio-char obtained from the pyrolysis was analyzed to modify the properties of asphalt binder and it was compared with commercially available activated carbon. It was found effective in improving resistance against rutting. It was also explored that bio-char yielded from finer switchgrass (particle size less than 75 μm) pyrolysis gave best resistance against cracking and fatigue. It was concluded that finer particle size of raw material and low heating ramp gave the best pyrolyzed material for modifying asphalt binder. It was also concluded that bio-char obtained via pyrolysis proved better than the commercially available activated carbon (Zhao et al., 2014). Bio-char from Lemna minor (aquatic biomass) was prepared via pyrolysis. It was noticed that pyrolysis temperature and rate of sweep gas flow have no significant effect on the pore volume and surface properties of bio-char. High surface area was achieved from elevated temperature (850 °C) CO_2 treated bio-char. Its inorganic ash content was higher than other agricultural residue and it was mainly consisted of silica and small amounts of Ca, Na, K, S and P. It also showed remarkable catalytic activity in bio-gas reforming reaction which needs further consideration (Muradov et al., 2012). The effect of raw material for pyrolysis on the characteristics of bio-char was studied. Micro carbon particles were prepared through pyrolysis using bamboo stems in four different raw forms. First pyrolysis was done on untreated and chemically treated bamboo stems (under atmospheric conditions, bamboo stems were soaked for 10days in aqueous solution of NaOH). Then to achieve more crystalline and enhanced graphitic form of these particles, these were annealed for 2 hours under inert atmosphere. Then these four types of carbonized materials obtained from bamboo stems were used in cement composite in different %age contents (Ahmad et al., 2015).

3. Utilization of synthesized carbonaceous inerts (bio-char)

3.1. Water treatment

The carbonaceous material obtained from the pyrolysis of soybean oil cake possesses good absorbent qualities and this activated carbon can be used for treatment of industrial wastewater and waste gases (Tay et al., 2009). The activated carbon obtained from the pyrolysis of bio mass can be used to clean industrial wastewater and waste gases (Uçar et al., 2009). Pb^{2+} and Cd^{2+} can be effectively removed from contaminated water using bio-chars achieved from the pyrolysis of oak wood and oak bar. These bio-chars concluded as cost effective and easily available material for water treatment (Mohan et al., 2014). Bio-char produced from the thermal liquefaction of rice husk with ethanol as solvent was rich in lactonic and carboxylic group. Ethanol bio-char rich in carboxylic group proved to be effective for removing malachite green from water (Leng, Yuan, Zeng, et al., 2015). Bio-chars produced from the thermochemical liquefaction method of sewage sludge in an autoclave reactor are found to be rich in oxygen-containing functional groups. This makes it effective in removing Methylene blue and Malachite green from aqueous solution (Leng, Yuan, Huang, et al., 2015).

3.2. Agricultural chemical

Bio-char can also be used as an addition to soil to enhance its fertility and to abate climate change by long term sequestration of carbon in soil at the same time (Lehmann et al., 2006). Significant carbon and nutrient minerals of residue corns were mostly present in bio-char which can make it a good agricultural chemical (Mullen et al., 2010). Fast pyrolysis of agricultural waste including wheat straw and flax straw as well as forest residue in form of sawdust and poultry litter that is an animal manure, resulted in the bio chars having high alkalinity. These bio-chars offer an excessive agricultural potential in comparison of other inorganic elements (Azargohar et al., 2014). The conversion of woody-wastes by pyrolysis to produce bio-char (biologically derived charcoal) is one potential option that can enhance natural rates of carbon sequestration in soils, reduce organic waste, and substitute renewable energy sources (McHenry, 2009).

3.3. As absorbents

High absorption capacity bio-chars, prepared via pyrolysis of corncobs and rice husk. chars can be inexpensive absorbents than fuel (W.-J. Liu et al., 2011). Fast pyrolysis was performed on oak wood and oak bar. Bio-chars obtained from the fast pyrolysis of oak wood and oak bar were found as potential green absorbents (Mohan et al., 2014).

3.4. As Solid fuel

The bio-char obtained from the pyrolysis of hornbeam saw dust has the calorific value of 32.88 MJ kg^{-1} making it a promising contender for solid fuel applications and an efficient substitute for renewable energy (Moralı, Yavuzel, & Şensöz, 2016).

3.5. Utilization in construction materials

3.5.1. Asphalt binder.

The carbonaceous material obtained from pyrolysis of switchgrass was utilized to modify the properties of asphalt binder. It was found more effective in improving resistance against rutting as compared to commercially available activated carbon. It was also explored that bio-char yielded from pyrolysis of finer switchgrass (particle size less than 75 µm) offered best resistance against cracking and fatigue. Finer particle size of raw material and low heating ramp gave the best pyrolysed material for modifying asphalt binder. Bio-char obtained via pyrolysis proved better than the commercially available activated carbon (Zhao et al., 2014).

3.5.2. Cementitious materials

An emerging new use of bio-char is to replace cement to a minor fraction to enhance mechanical as well as electrical properties of cementitious system. Ferro et. al. started utilization of bio-char prepared in cementitious composites to enhance their mechanical properties. He prepared carbon micro/nano particles via controlled pyrolysis of coconut coir. On addition up to 0.08% by weight of cement in cement composites, it gave improved compressive strength and fracture toughness. The presence of these micro/nano particles forced the crack to follow their contours instead of straight trajectory, increasing the energy required to fail the sample (G. Ferro et al., 2015). Ferro also prepared carbonized inerts from pyrolysis of hemp herds (an agricultural waste), and then these inerts were grounded to nano size and added into cementitious system. On addition of just 0.08% of this bio-char in nano sized range increased the modulus of rupture. Toughness indices were obtained maximum for 3% replacement of these inerts in cement based system. Compressive strength was also improved with the addition of this bio-char and the maximum compressive strength was achieved for 1% inert replacement. These particles acted as obstacles in the path of cracks, and it was visually noticed that areas of fracture surface of composite containing inert was several times more than the controlled one, which was responsible for improved mechanical properties of cement composites. Finally it was concluded that carbonized nano particles obtained from pyrolysis of hemp herd are quite efficient in enhancing the fracture toughness and compressive strength of cement composites. (G. A. Ferro et al., 2014).

Later, Khushnood. et al. intruded the bio-char obtained from the pyrolysis of peanut shells and hazel nuts shells (agricultural waste) in micro-nano size range in cement paste and mortar and achieved improve shielding of cement composite against electromagnetic interference. It was explored that these materials were not only cheap (cost saving > 85%) than the previously used carbon nanotubes (CNTs) and graphene; rather their dispersion in water and host medium was also good and easily achievable. The better electromagnetic shielding was due to excellent dispersion of carbonized particles in the cement composites. Carbonized peanut shell gave a little better result than carbonized peanut shell, due to more specific surface area, or in other words because of more particles dispersed in the cement composite for the same %age of inert replaced with cement (Khushnood et al., 2015).

Ahmad et. al. prepared four different types of bio chars from the pyrolysis of bamboo stem. Then these four types of carbonized materials obtained from bamboo stems were used in cement composite in different %ages (i.e. 0.05%, 0.08% and 0.2%) and their mechanical properties were compared with controlled sample (i.e. with 0% replacement of cement with carbonized particles). Inclusion of all these four micro carbonized particles in cementitious material improved their toughness, compressive and flexural strength. Best results were obtained for 0.08% inclusion. These particles dispersed well and increased the fracture surface area by diverting the crack path, thus improved energy absorption capacity and more post peak load carrying were achieved (Ahmad et al., 2015).

The bio-chars obtained from pyrolysis of hazelnut shells and coffee powders, grounded to nano size, were replaced in different percentages of cement content in cementitious materials. These carbon nanoparticles also enhanced the compressive and flexural strength along with fracture energy. The carbon nanoparticles not only increased the ultimate fracture area by making the crack path tortuous but also escalated the hydration of cement resulting in improved mechanical properties (Restuccia & Ferro, 2016).

Akhtar et. al. also utilized bio-char to modify the mechanical properties of cement mortar by. Bio-char prepared from organic waste when added to cement mortar give significance enhancement in compressive strength, split tensile strength. Microstructure was also improved on addition of bio-chars to a certain amount and addition of further content of bio-char resulted in large pores were found in the matrix giving high water absorption. The addition of bio-char contributes in the filling and packing rather than pozzolanic behavior, showing the aptitude of producing compact structures contributing a little in chemical enhancement (Akhtar & Sarmah, 2018).

Recently Gupta et. al. intruded bio-char obtained from the pyrolysis of wood saw dust in cement mortar and investigated the effects of this addition on the mechanical properties of cementitious system. In this study it was recommended that bio-char can be utilized to improve strength and reduce permeability of cement mortar (Gupta, Kua, et al., 2018a). In another study, Gupta et. al. also used the same bio-char as an immobilizer to carry bacteria in self-healing concrete. This study elucidated that the bacteria immobilized through bio-char has potential to produce excellent self-healing concrete that has an ability to seal cracks and recover strength (Gupta, Kua, & Dai Pang, 2018b).

3.6. Utilization in producing sensors

The bio-char has found its way in the synthesis of low cost, highly accurate reproducible and sustainable humidity and electrical sensors. Generally, the working principle of sensors is based on the thermal conductance, capacitance and electrical resistance. The inclusion of carbonaceous inerts may exhibit sensible resistance in the resulting composites at various humidity levels. Ahmed et. al. reported that the carbonized bamboo particles based humidity sensors may exhibit excellent response in the relative humidity ranging from 10 to 96% with minimal recovery periods at room temperature These efficient sensing characteristics may be attributed to the higher surface area of the carbonized particles and strong adsorption nature (Afify et al., 2017). Zeigler et. al. reported the use of carbonaceous inerts prepared from oil seed rape and soft wood pellets in the manufacturing of efficient humidity sensors. The Polyvinylpyrrolidone was used as polymeric binder with the carbonaceous inerts leading to the stability and durability of the humidity sensors at elevated temperature (Zeigler et. al ., 2017).

4. Future novel applications

Based on the observations from the literature, bio-chars may have many more future novel applications. Bio-chars obtained from the pyrolysis of organic waste other than woody wastes can also be utilized as an immobilizer for carrying bacterial solution into cementitious system to make it self-healing cementitious system. As bio-chars produced from the wastes have porous structure, these can also be utilized as absorbents for internal curing of the high-performance concrete where autogenous shrinkage is a major concern due to high content of cement and low content of water. Furthermore, pyrolysis of some other wastes also needs to be done to explore their potential applications for different useful purposes.

5. Conclusions

Following conclusions can be drawn based on the extension review of literature

[1]. For a high bio-char production from pyrolysis of organic waste, a low temperature and low heating rate process would be chosen.
[2]. For high quality bio-char production, high temperature of pyrolysis will be the absolute option
[3]. Carbonaceous material produced from pyrolysis of organic waste is a promising candidate for low cost waste water treatment.
[4]. Bio-chars can be utilized as means of abating climate change by sequestering carbon in soil increasing fertility of soil as well as utilizing carbon in a safer way as these bio-chars have high volume of carbon stored during pyrolysis and ultimately reduce the addition of CO_2 in atmosphere.
[5]. Carbonaceous material in form of bio-char has the potential to be successfully deployed as a carbon sequestering addition in concrete constructions to improve the performance of cementitious system mechanically and electrically and also provide a way to waste recycling.

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