Sustainable and self-sensing concrete

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SUSTAINABLE AND SELF-SENSING CONCRETE

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ABSTRACT: The majority of civil infrastructure is constructed using concrete materials and currently concrete production is at all time high resulting in significant carbon dioxide emissions. Furthermore, concrete structures have low tensile strength and low ductility increasing the risk of failure. Therefore concrete is currently neither environmentally nor economically sustainable. This experimental investigation has been highly promising in identifying an alternative solution to solve the sustainability issue regarding concrete. Our critical literature showed that there have been successful in identifying the most optimum solution to solve the issue of carbon dioxide emissions related to concrete production but concrete structures still lacks of self-monitoring ability for failure or any changes in the structure. This paper will identify the factors that influence the self-monitoring ability as mainly the conductive filler, fabrication and dispersion, which are the critical parameters. Experimental study has been carried out to identify the most environmentally sustainable solution with a minimum of 40MPa strength; over 30 concrete mixtures were tested for compressive strength at 28 days. We found that the R7.5S60SF mix with CNT (Carbon nano tubes) has the self-monitoring ability and reduces carbon dioxide emissions by 140kg per meter cubed of concrete produced in comparison to a meter cubed of ordinary Portland cement concrete.

KEYWORDS: Concrete, Sustainable material, Self-sensing; Self-monitoring; Innovative material; Carbon nanotube

1. Introduction

The majority of civil infrastructure is constructed out of concrete, currently at a rate of 2 billion tonnes per year; this is responsible for 5% of global carbon dioxide emissions annually [1]. Despite the high usage, concrete has several disadvantages such as low tensile strength, low ductility and high susceptibility to cracking. This causes the structure to deteriorate and lose its integrity when subjected to harsh environmental conditions or loading [2]. Thus, when exposed to these conditions, concrete structures are at a risk of failure. The high global usage of concrete combined with the large amount of pollution produced every year is also a major concern. Therefore a sustainable approach needs to be taken to find solution to these existing issues in concrete production. The sustainable approach within this project involves developing a method to reduce carbon emissions and to improve the resilience of concrete structures.

Numerous approaches have been taken for centuries to enhance the properties of concrete. Previously, there has been a breakthrough in concrete development by Chung [2] introducing self-monitoring concrete. The self-monitoring ability implemented into concrete permits the assessment of safety and resilience of the structure throughout its service life - this ensures the structure remains serviceable [3]. This self-monitoring ability is owed to conductive fillers, for example carbon nanotubes (CNT). Therefore, it would be of great advantage to identify a conductive filler that enhances the properties of concrete along with developing a concrete mix, which minimises environmental impact. An approach that can be taken is to minimise the use of cement, which is a significant contributor to carbon emissions during its manufacturing process [4-5]. Hence, the aim of this study is to identify a concrete mixture, which is able to self-monitor as well as reduce carbon emissions.

The study comprises firstly of a literature review, which discusses existing concrete mixtures containing waste materials for the purposes of reducing carbon emissions and also outlining the significance of self-monitoring concrete and a superior conductive filler. The literature review is used to provide guidance to create a methodology, which in turn develops a series of concrete mixtures for strength testing at 28 days. This is to identify a superior mix which does not only reduce carbon emissions but also has significant compressive strength i.e. 40 MPa, which is the minimum required strength to be classified as high strength concrete [6]. Once a superior mix is identified, appropriate conductive filler will be added to this to implement the self-monitoring ability. This superior mix containing the conductive filler will be tested for numerous mechanical properties. The results obtained from these tests will be presented and compared to results obtained from a control mix. Once the results are obtained they will be critically analysed and will be compared against experimental results from existing literature. Finally, recommendations for application and improvement of the superior mix with conductive filer will be presented. The main aim of this research is to develop a concrete mixture, which reduces environmental impact and has self-monitoring ability.

2. Previous studies

Initially, a concrete mix that reduces carbon emissions in comparison to ordinary Portland cement concrete (OPCC) is identified, thus creating a environmentally sustainable variant without deteriorating properties of OPCC significantly. The method to make such an environmentally sustainable concrete is to replace components of OPCC with waste materials in order to reduce carbon emissions. This approach is based on the assertion that primary materials of production are more greatly responsible for carbon emissions rather than waste materials of production. Also some of the waste materials are less carbon dioxide emission intensive in comparison to cement. Extensive research has already been carried out in making concrete environmentally sustainable. There are many alternative methods presented for substitution of cement and aggregates. The most common substitutes for cement are ground granulated blast-furnace slag (GGBS), silica fume and fly ash, and for aggregate are glass and rubber.

2.1 Ground Granulated Blast Furnace Slag

The UK generates 2.2 million tonnes of GGBS, a waste material of the iron industry; instead of sending it to landfill, countless experimental studies have been carried out which establish GGBS as a cementitious substitute [7]. Topçu [8] reviewed literature based on GGBS. It has a high calcium silicate content, which makes it an excellent material to replace ordinary Portland cement (OPC). The disadvantages of partially replacing OPC with GGBS in OPCC leads to lower short-term strength (14 day strength), longer curing period, and increased shrinkage and cracking. There are many benefits of partially replacing OPC with GGBS; some of the benefits are greater long-term strength (after 28 days), less creep, better workability, and greater resistance to chloride and sulphate attack. These findings are valid and therefore accepted because Topcu (2013) supported these statements with a range of experimental studies. Güneyisi and Gesoğlu [9] conducted a study using different proportions of GGBS. Up to 60% replacement of OPC with GGBS show improved compressive strength in comparison to OPCC. Above 60% there is a decrease in compressive strength. Therefore, GGBS can partially replace OPC cement; hence reduction in production of OPC and CO_2 emissions can be achieved. However another researcher has not validated these assertions.

2.2 Silica Fume

Silica fume, a by-product of the silicon industry, has been proven as an additive by countless experimental studies to develop and produce high strength concrete. An extensive literature review carried out by Khan and Siddique [10] shows that 10% replacement of cement with silica fume improves the mechanical and chemical properties of concrete. The replacement does not only improve compressive strength but also increases resistance to corrosion, reduces the effects of freezing and thawing as well as other benefits. Above 10%, the properties of concrete are not further enhanced and detrimental effects such as corrosion, cracking and spalling occur. Due to these beneficial properties, silica fume is widely used in the concrete industry [11-12].

2.3 Fly Ash

So called "Green Concrete" mixtures have been produced, which replace cement entirely with fly ash. The experimental fly ash concrete results were promising, showing it is feasible to make concrete with fly ash [13]. However fly ash is currently a waste material of the coal industry. The coal industry is declining rapidly, as there is a strong shift towards renewable energy and nuclear energy power [14]. With this declining industry, there will simultaneously be diminishing supply of fly ash to be used in production of concrete. Therefore based on the security of future supply of fly ash, it is deemed to be not a sustainable material. Hence this study does not focus on the use of fly ash as a substitute for OPC.

2.4 Tyre Rubber

The UK generates around 55 million waste tyres annually that are not recycled, as shown in Fig. 1 [7]. Instead of sending the waste to landfill, the tyres can be processed by mechanical means and converted to crumb rubber. This can be used to replace proportions of fine aggregate in concrete mixtures [15]. Tyres are an environmental hazard; they are an ecological threat that can cause a reduction in biodiversity, as they are known to leachate into water and affect the aquatic life forms. This problem can be addressed by recycling tyre rubber into concrete, where it will remain inert and cause no harm to ecosystems. It is a step towards making the UK and the world more sustainable. Various experimental studies have been already conducted, where rubber is used as an aggregate. A large number experimental of studies show that increasing the rubber content reduces strength such as works of Güneyisi et al. [16] and Ghaly and Cahill IV [17]. However experimental study conducted by Ghaly and Cahill IV [17] shows, 40MPa strength can still be achieved when replacing 10% fine aggregate by volume with rubber. It is a reliable study as they tested over 180 samples of different rubber based concrete mixtures and also the study by Güneyisi et al. [16] shows the same correlation where the tested over 70 samples. They both show the same correlation that increasing rubber content reduces strength, therefore the findings are in agreement and can be held true. Another recent experimental study [13] validates their findings and additionally finds that 5% to 10% of crumb rubber with silica fume is able to produce concrete with a compressive strength above 40MPa.

2.5 Combination of GGBS, Tyres and Silica fume or substitutes

Gupta et al. [18] carried out an experimental study and found that replacing cement with 50% copper slag and fine aggregate with 10% tyre rubber by volume gives a compressive strength of

30MPa. The study shows the feasibility of slag and tyre concrete mix to be used as structural concrete. However the study uses copper slag but this research study focuses on GGBS, therefore it is not a reliable study to accurately estimate the effects of GGBS, as they are two different materials. Experimental study would need to be undertaken with GGBS, sourced from steel production, to validate the hypothesis of the use of slag and tyre. Therefore this study will initially focus on creating a mixture, which replaces significant proportion of cement with GGBS, fine aggregate with rubber and has a minimum compressive strength of 40MPa at 28 days. This will help achieve environmental sustainability in term of concrete production. Economical sustainability can be achieved by ensuring the structure lasts for a long period, this is ensured via an effective monitoring method, such as incorporating the self- monitoring ability.

Fig.1. Waste Tyres

2.6 Self-monitoring Concrete

In the past two decades there has been considerable progression in the development of self- monitoring concrete. Initial studies showed that a self-monitoring cement composite has the ability to sense any applied strain and damage [1]. The conclusions made by Chung [1] over 20 years ago are valid and true as they are the fundamental principles of the self- monitoring ability. Recently there has been advancement in research and now the self-monitoring ability is not only limited to sensing strain, but also stress, cracks and dynamic loading [19].

OPCC does not have the ability to conduct electricity; however adding conductive fillers, such as carbon fibre allows electrical conduction thus providing the ability to self-monitor [1-2]. Electricity is conducted through the conductive filler concrete composite via electronic and/or hole conduction and ionic conduction, due to the cement concrete matrix [19]. However there is no need for a large addition of conductive filler for the material to be conductive. For example, an experimental study concluded that the cement composite containing carbon fibre of only 0.2% showed the self-monitoring ability - this is below the percolation threshold of 1%, so there is no need for fibres to be touching [1]. Intuitively, it may be considered a full continuous circuit without any breaks is required to conduct electricity; therefore percolation threshold guarantees a complete chain in the material. However, an experimental study by Chung [1] showed that a full circuit does not need to be present for electrical conduction to take place. Other researchers such as Azhari and Banthia (2012) obtained similar results, which supported this conclusion.

There are a number of functional fillers, which can be used to give concrete the self-monitoring capability such as carbon fibre, CNT, steel fibre, carbon black and steel slag. For superior sensing ability, cement composite can be made up of two or more fillers [19]. The self-monitoring ability is beneficial for maintenance and identifying the serviceable life of a concrete structure. This is due to the change in electrical properties of a material, when there is a change in properties of the conductive concrete composite such as strain and stress.

2.7 Carbon nanotubes and their applications in concrete

Table 1 summarises the properties of a few fibrous materials, which can improve properties of concrete. It can be clearly seen that CNT is a superior material in comparison to other materials such as high strength steel, carbon fibre, glass and Kevlar.

Carbon fibre and CNT are comparable due to their similar chemical composition. Experiments show CNTs have a higher thermal conductivity (>3000 W/m.K) in comparison to carbon fibre (1000 W/m.K) and copper (400 W/m.K) [20]. When electricity is conducted through the CNT cement composite, the CNT will be able to dissipate the generated heat quickly. If heat is allowed to build up, it can have a negative effect on the concrete, for example causing expansion, resulting in cracks. The low electrical conductivity compared to copper and carbon fibre is beneficial.

A highly conductive material can cause the material to have extremely low resistivity, resulting in a considerably small change in resistance, making it extremely difficult to detect any change in strain [2].

CNT is a good material due to its mechanical properties. However, CNT has a lattice structure, which has imperfections. Experimental study shows that this adversely affecting the mechanical strength developed. However, experimental study shows the defects can be beneficial as they provide sites for a chemical to be attached which can provide better chemical bonding between CNTs and cementitious matrix (Ferro et al. 2011). CNTs are highly flexible with a high aspect ratio increasing the probability of fibres getting tangled and forming agglomerates [19]. Also CNTs have a large amount of Van der Waal's forces resulting in close packing (Ferro et al., 2011). Therefore dispersion is a pertinent issue when adding CNT to cement composite, as it is a main factor which reduces the performance of the self-monitoring concrete. Several methods and materials have been studied to be able to uniformly distribute CNT and other functional fillers in cement composite.

Table 1 Properties of fibrous materials.

Fibre Material	Specific Density	E (TPa)	Strength (GPa)	Ultimate Strain (%)
Carbon Nanotube	1.3-2.0	1.0	10-60	10
HS Steel	7.8	0.2	4.1	<10
Carbon Fibre – PAN	1.7-2.0	0.2-0.6	1.7-5	0.3-2.4
Carbon Fibre – Pitch	2-3.2	0.4-0.96	2.2	0.27-0.60
E/S – glass	2.5	0.07	2.4	4.8
Kevlar 49	1.4	0.13	3.6-5.1	2.8

CNT can be dispersed via mechanical and/or chemical methods. A theoretical study states that physical methods such as high shear mixing separates fillers but fragments fibrous fillers [19]. Chemically, CNTs are hydrophobic, which is a problem because it does not disperse in water. So chemical methods can be used to alter the surface structure to help make it more soluble and dispersible.

Implementing carbon nanotubes into a superior mix made up of GGBS, rubber and silica fume is a feasible approach. This mix to a high extent solves the issue of environmental impact that cement has, along with addressing the issue of resilience of concrete structures. So far the existing experimental literature has not explored this approach. At the same time, there are numerous claims made on the advancement and monitoring of self-monitoring concrete but fail to address the issue of carbon emissions via experimental study. There is an existing study, which considers the approach of implementing waste material with carbon nanotubes theoretically but fails to carry out an experimental study to validate their hypothesis. This research project will try to experimentally validate the feasibility of adding GGBS, silica fume, rubber and carbon nanotubes to concrete mix.

3. Materials

In this study the raw materials used to create test specimens are cement, water, gravel, sand, GGBS, Rubber, silica fume, LASS and CNT. Cement, GGBS, Rubber, silica fume, LASS and CNT are stored in airtight containers, to prevent any moisture getting in.

3.1 Cement

OPC type-1 is used, which is in accordance with British Standards code EN 197-1 with a characteristic strength of 52.5MPa at 28 days.

3.2 Water

Clean, potable water from the laboratory tap is used in mixtures for the hydration of cement.

3.3 Coarse and Fine Aggregate

Crushed gravel with a maximum particle size of 20mm was used as coarse aggregate. Natural sand with a maximum particle size of 10mm was used as fine aggregate. The water content of gravel and sand is measured by initially weighing 100g of each aggregate sample. Secondly, the sample was heated and then the surface dryness was ensured by visual inspection. After the sample is surface dry, the change in weight is measured. The change in weight was used to adjust the water content for concrete mixtures to be created.

3.4 Carbon Nanotubes

The CNT type used is MWCNT. Characteristics of these MWCNTs are as follows: surface area is 250-300m2/g; metal oxide 10%; carbon purity 90%; average nanotube length 1.5 micrometres and average diameter is 9.5 nanometre. For experimentation 2% carbon nanotubes will be used by weight of cement. As there is only one experimental study conducted by Sovják et al. [21], which investigates the optimum amount of conductive filler as 2%. Nanocyl, Belgium supplied the carbon nanotubes and is marketed as model – nc 7000.

3.5 Ground Granulated Blast-furnace Slag

Ground granulated blast-furnace slag (GGBS) is a white coloured powder, which is used to replace certain proportions of cement. It is supplied by Hanson and marketed as Regen-GGBS.

3.6 Silica Fume

Silica fume a fine grey powder, grade 940 was used in this study. Elkem supplied the product; it is marketed as microsilica – grade 940.

3.7 Crumb Rubber

75 micron crumb rubber was used based on the study by Meesit (2015). As the experimental study outlines that 75 micron rubber, produces higher strength concrete in comparison to other particle sizes. It is sourced from grinding waste tyres. The crumb rubber is free of any contaminants such as metals, dust, fabrics and etc. The provider of materials is J. Allcock & Sons Ltd.

3.8 Ligno-Sulfonic Acid Sodium Salt

LASS is a dispersant; it is used in mixtures containing CNTs. LASS was supplied by Sigmaaldrich Ltd.

3.9 Copper Mesh

Copper mesh with a mesh spacing of 25cm by 25cm. It is supplied by Oasis, marketed as copper floral mesh.

4. Concrete Mix Design

The design of concrete mixtures is designed using the guidance provided in 'Design of Normal Concrete Mixes' [22]. The control concrete mix, which is the standard OPCC mix with a target mean strength of 53 MPa at 28-days, is designed using this guidance. All mixtures are based on the reference concrete mix. 30 different sustainable mixtures are developed. Each mixture contains varying amounts of GGBS between 20 and 60%, rubber 5 to 10% and/or 10% silica fume. After conducting a 28-day compressive strength study on all 30 mixtures, data was collected and can be compared. From the 30 mixtures, R7.5S60SF was chosen as the superior mix for further study. The R7.5S60SF mix replaces constituents of the control mix (refer to Table 2) as follows: 70% cement with 60% GGBS and 10% with silica fume; and 7.5% of fine aggregate with rubber in OPCC. This mix is chosen as the superior mix because this mix replaced the highest amount of cement, replaced some of natural aggregate with waste material, further meeting the criteria of minimum strength of 40MPa. The R7.5S60SF replaces cement with 70% waste material; this proportion was also selected because there is reduction of 140kg of CO_2 emissions per meter cubed of concrete produced [22]. For the implementation of the self-monitoring ability, a CNT-variant of control mixture and R7.5S60SF are produced, replacing fine aggregate. This study will mainly focus on the mixtures outlined in Table 2.

Table 2 Proportion of materials in each mix.

Mix	Units - kg/m^3								
	Cement	Water	Gravel	Sand	Rubber	Slag	Silica Fume	LASS	CNT
Control	530	233	986	630	-	-	-		
R7.5S60SF	159	233	986	583	47.25	318	53		
Control + CNT	530	233	986	608.8	-	-	-	10.6	10.6
R7.5S60SF + CNT	159	233	986	562	47.25	318	53	10.6	10.6

The whole process of mixing CNT is summarised in the Fig. 2. Samples containing MWCNT are created as follows. Once the CNT, dispersant and water mixture are created following Fig. 2, the CNT and dispersant are added in same manner as water in normal mixtures through the viewing window of the mechanical mixer.

The casting process for the 30 mixtures mentioned earlier uses a 100mm cube mould. The mould shape and dimensions for the optimal solution R7.7S60SF and control mix is cube (100 mm x 100 mm x 100 mm), cylinder (100mm diameter and 200mm length) and prism (100 mm x 100 mm x 500 mm). The purpose of using these specific mould shapes and dimensions is due to the availability of moulds in laboratory, as well as adhering to British Standards EN 12390-3, British Standards EN 12390-6 and British standards EN 12390-5 for testing purposes.

Once the samples are casted they are covered with a polythene sheet for 24 hours. The polythene sheet is used to reduce moisture loss. After the moulds have been cured for 24 hours, they are carefully removed from the mould and placed in water tank. The water tank is at a temperature of 20 degrees Celsius, the laboratory temperature, where they will set and cure until required for testing.

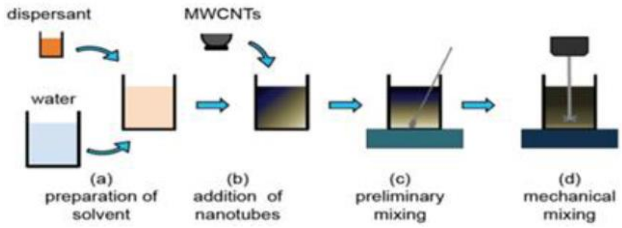

Fig.2. Mixing process

5. Testing Methods

Compressive strength test has been carried out in accordance to BS EN 12390-3 on the cube samples. For monotonic testing, the specimen is placed into the Denison machine that applies a constantly increasing load at a rate of 0.1 MPa.s-1 until the failure of the specimen. The specimens containing CNT undergo electrical resistivity measurement. The purpose of measuring electrical resistivity is to determine the presence of the self-monitoring ability in the concrete mix. A multi-metre is connected to the copper mesh to continuously record change in voltage during compressive strength testing. The flexural strength testing has also been carried out respectively in accordance to BS EN 1290-5 [22].

To assess the workability of the superior mixture and control mix, the slump of the mix needs to be measured. Slump measurements are carried out in accordance to BS EN 12350-2. Slump cone and a metal board is cleaned and moistened. The slump cone is filled with the concrete mixture in 3 layers. Each layer is compacted with a striking rod with 25 strokes. Once the third layer is added a clean finish is given using a trowel. Using a slow twisting motion upwards the cone is removed. The cone is turned upside down and the rod is placed on top of cone. The gap between the rod and the slump is measured. The height recorded is the slump of the mixture.

6. Results and discussion

Slump testing was carried out as stated in Section 5 on all the samples mentioned in Table 2. All the concrete mixtures were observed by visual inspection to be cohesive with no presence of segregation or bleeding during the mixing, placing or compaction. Fig. 3 shows the slump values obtained from all the tested mixtures. The highest slump recorded was 105 of the control mix. The Control mix + CNT, R7.5S60SF, R7.5S60SF + CNT had slump values of 20% (21 mm), 35% (37 mm) and 49% (51 mm) lower than that of control mix. It is interpreted from these results that this reduction in slump is due to the components of the control mix being replaced; as the proportion of replaced component increases, the slump decreases. The control mix was designed with a slump of 60-180mm.

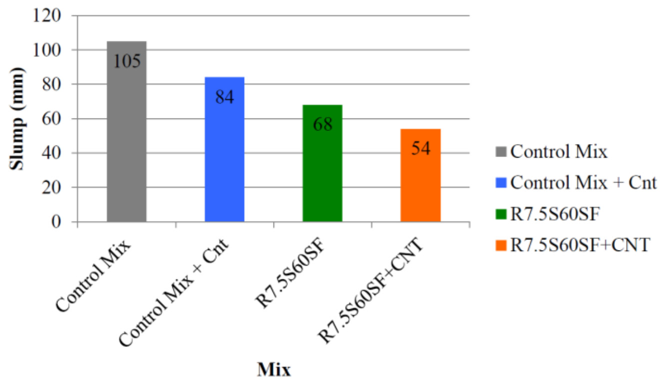

Fig.3. Slump of concrete mixes

Assessing each mix individually helps to understand the observed results. The control mix with CNT has a reduction in slump compared to control mix. This result was highly expected as some previous experimental studies have outlined reduction in workability when adding CNT. On of the first experimental studies [5, 6] showed a reduction in slump when adding even 0.5% MWCNT. The workability of concrete mixtures containing CNT was further investigated [6]. The results have been similar in both of these studies, showing a reduction in slump. The result in reduction in slump is attributed to the large surface area of MWCNT, which introduces a greater amount of surface interaction within the mix. The results obtained are in agreement with previous studies when CNT is added to the control mix. The mix having a slump of 84mm is not near the lower limit value of workability of 60mm; therefore it is easy to work with this mix.

In terms of the R7.5S60SF mix, no previous study has investigated the workability of concrete containing GGBS, rubber and silica fume. However the components of the mix can be assessed individually to assess the effect on workability. Recent studies [10] on the effect of rubber on workability correlate with results obtained in Fig. 3 as they both show a reduction in slump in comparison to control mix. The reason for the result obtained in reduction of slump is due to the higher water absorption by the rubber particles in comparison to sand, these results in reduction in availability of free water, resulting in a more viscous mix. The result in Fig. 3 for the R7.5S60SF mixture correlates with existing literature. This mixture has a workability of 64 mm, which is near the lower limit. Hence it is considered not to be a highly workable mix but acceptable as it is still within the design limit.

The compressive strength testing was carried out as specified in Section 5 on the mixtures mentioned in Table 2. All test specimens were surface dry before testing. The compressive strength results are outlined below in Fig. 4. The highest compressive strength value was obtained by the control mix with strength value of 56.40MPA. The control mix with CNT, R7.5S60SF and R7.5S60SF with CNT had compressive strength values of 2.8% (1.6 MPa), 21.3% (12 MPa) and 27% (MPa) lower than the control mix, respectively.

The compressive strength of the control mix with CNT does not conform to existing literature. This is because the existing literature suggests an improvement in compressive strength when carbon nanotubes are added. The experimental study carried out by Eftekhari and Mohammadi [23] shows a 26% increase in compressive strength when CNTare added. The results obtained do not correlate with existing literature. Another study, which also indicates an increase in strength, is that of Sovják et al. [21] found an increase in strength in comparison to the control mix when CNT are added. There is not enough literature available and the results do not have a strong correlation to indicate the CNT affects the compressive strength hence the effect of CNT on the mixture compressive strength is inconclusive. Based on the result in Fig. 4, it can be concluded that 60% GGBS and 7.5% inclusion of rubber leads to a reduction in strength. However it is inconclusive to what extent each material affects the strength.

The flexural strength testing was carried out as detailed in Section 5 on the mixtures stated in Table 2. All test specimens were surface dry before commencing testing. The results obtained from flexural tensile strength testing are presented in Fig. 5. The highest value recorded was for the control mix with CNT at 5MPa. The control mix, R7.5S6060SF mix and R7.5S60SF mix with CNT had flexural tensile strength values lower than that of the control mix with CNT of 2.2% (0.11 MPa), 18% (1.0 MPa) and 5.9% (0.29MPa) respectively. It can be interpreted that adding 7.5% rubber and 60% slag results in reduction in tensile strength. These results correlate with the one and only experimental study conducted by Gupta et al. [18] who found that adding 5% rubber and 40% copper slag results in a reduction in tensile strength. The experimental studies are not identical as one use copper slag and the research project uses GGBS. However the properties of copper slag and GGBS are similar and the results in Fig. 5 and the study conducted by Gupta et al. [18] show a similar correlation. Therefore it can be concluded that adding rubber and GGBS result in a reduction in strength.

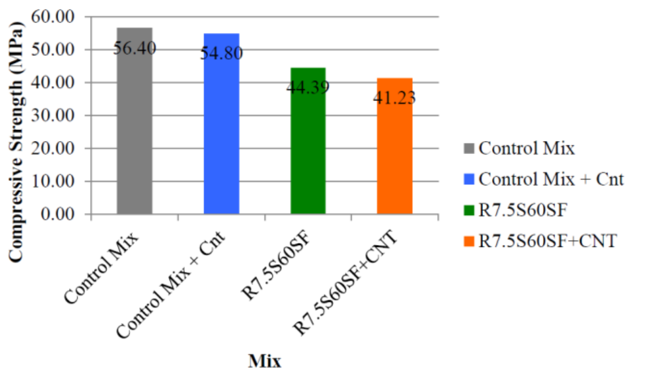

Fig.4. Compressive strengths of concrete mixes

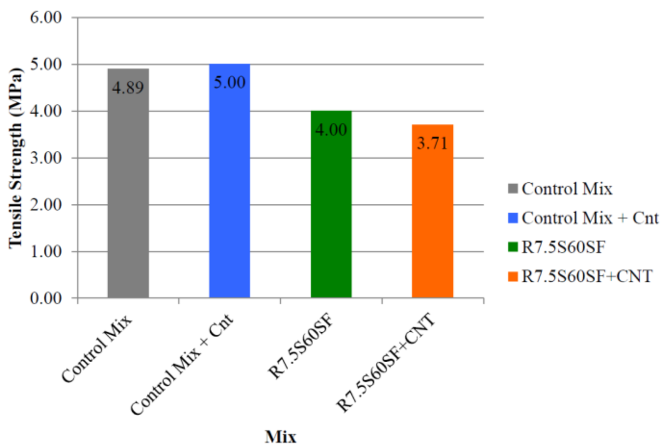

Fig.5. Flexural strengths of concrete mixes

Based on our experimental results, the flexural strength results obtained are inconclusive to comment on the effect of CNT on flexural strength.

Electrical resistivity helps to assess the self-monitoring ability of the samples. The recording of electrical resistivity was carried out and processed on the control mix with CNT and the R7.5S60SF mix with CNT. The electrical resistivity measurement was only conducted on these materials as adding CNT provides electrical conductivity. The processed results are presented in Fig. 6.

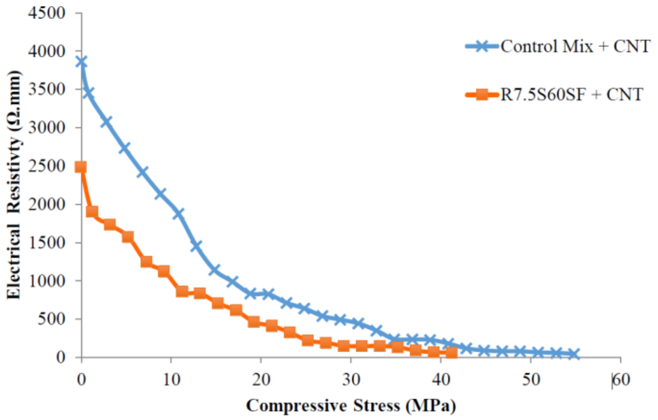

Fig.6. Change in electrical resistivity of concrete subjected to compression

Normally concrete has a very high electrical resistivity, for example in order of 100000 Ω.mm, therefore a change in resistivity will not be significant enough to be detected if loading is applied (Collins, 2016). The results show a strong correlation for both mixtures, increasing compressive strength reduces electrical resistivity of the sample. This result can be attributed to the carbon nanotubes as countless studies on cement composites have been carried out by for example, Chung [1], Chung [2] and Ubertini et. al [3] and Azhari and Banthia [24]. This is because when loading is applied, the specimen undergoes compression, bringing the carbon nanotubes closer, thus reducing the electrical resistivity as mentioned earlier. This conclusion applies to both of the mixtures under investigation in Fig. 6. Based on the obtained results, it is important to note that the electrical resistivity for both mixtures seems to plateau as it reaches the failure mode.

Conclusions

In conclusion, this experimental investigation has been highly promising in identifying a solution to solve the sustainability issue regarding concrete. The desk study identifies that combination of waste materials can be used to replace cement and aggregate in a concrete mix and conductive filler can be added to provide self-monitoring ability. The initial experimental study of compressive strength identifies a mix, which contains GGBS, rubber and silica fume. This mix has significant strength and replaces a large amount of cement and addition of rubber for fine aggregate. The GGBS, rubber and slag mix reduces carbon dioxide emissions, making the concrete produced environmentally sustainable. The main focus of this study is identifying some of the properties of this mix and implementing the self-monitoring ability. The factor that influences the self-monitoring ability is mainly dispersion and the conductive filler. CNT was chosen as the conductive filler as they were identified to have excellent mechanical and electrical properties. The experimental study investigates the workability, compressive strength, flexural strength and electrical resistivity. The main conclusion that can be summarised from the results obtained is that slag, rubber and silica fume can be added to a mix along with carbon nanotubes to create self-monitoring concrete because the results shows a reduction in electrical resistivity when compressive loading is applied. Addition of slag and/or rubber reduces the strength, however the reason behind the loss of strength is currently unknown.

Future work includes detailed investigation to be carried out to understand the interaction between carbon nanotubes and waste materials in concrete and their effects on the physical and mechanical properties. The workability of the sustainable and self-monitoring mix could be an important practical issue, thus to solve the problem of workability, a plasticiser could be introduced to the mix and improve the workability, however the feasibility of such a mix would need to be assessed.

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