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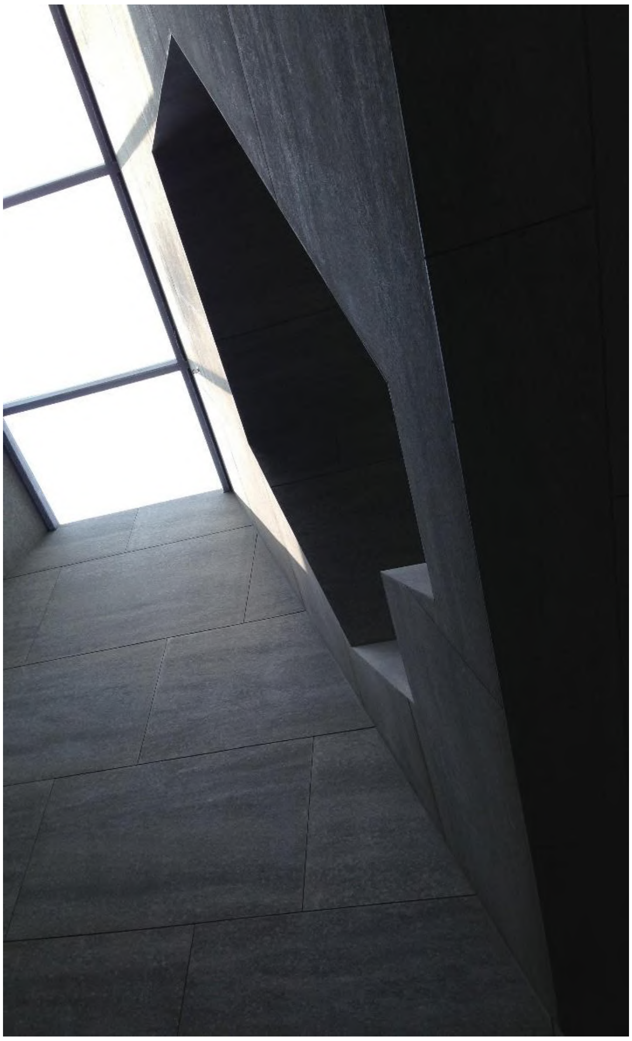

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Use of the by-products of post-combustion carbon capture in concrete production: Australian case study

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Abstract

Australia as one of the pioneers in the adoption of green industries, had made significant steps in zero emission programs. Post-combustion, pre-combustion, and Oxy-fuel combustion are three conventional techniques for capturing the CO_2 gas from the coal-fired power generation plants. Since almost 50% of the electricity generation is derived from the coal power plants in Australia, it is important to pinpoint the progress made in carbon capture and storage technologies throughout the last decade. This paper, firstly, reviews the advancements in the carbon capture and storage technologies in Australia by considering the pros and cons in the adoption of each of the 3 major techniques in detail. It can be of advantage for other economies in the world to adopt the presented workflow as lessons to be taken. Also, as the CO_2 storage after the capturing process is one of the challenges facing the industry, the current study, secondly, presents a new practical method to consume the captured CO_2 in construction activities specially in concrete production by promoting a new type of chemical admixture. Experimental laboratory studies show satisfying results in the utilization of the carbon capture product in concrete production. A survey had also been conducted that matches the supply and demand of recycled aggregate in the selected region showcasing the financial viability for commercializing this product.

Keywords

CO2 capture; Post-combustion Capture; Construction and demolition Waste; Chemical Admixture; Sustainable development

Introduction

For many years now, the emission of greenhouse gases had become one of the main concerns of almost any developing industry. The atmospheric concentration of the greenhouse gases is increasing due to the increase in the population of Earth and the associated human activities. Carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide are amongst the greenhouses gases that the emission of which in total is resulting in the addition of the warming of the earth's surface[1]. Report published by the international energy agency estimates the global reach of CO_2 emission to 45 gigatonnes by 2035 which solely correlates with a 5.6°C rise in the earth's temperature[2]. There are more than 100 countries that adopted the practices in the mitigation of efforts to reduce the climate change[3] where Australia is one of the leaders amongst the participants. In 2019, the Federal Government of Australia has devoted a $2 billion budget for environmental carbon footprint reduction[4]. It is known that the energy sector is one of the main sources of carbon emission all over the world. Thus, it is, first, necessary to address the efficiency of the Australian energy suppliers along the carbon capturing plans.

Following the novelty of this article, as the construction industry is also being categorized as one of the main pollutant industries globally, upon the progress of this research satisfactory results had been achieved from the laboratory test. The tests were design to evaluate the performance of a new concrete chemical admixture which is produced for the purpose of enhancing the rheology of concrete made with recycled aggregate. The so-called admixture compromises chemical absorption of CO_2 gas as part of the production process. Concrete samples had been tested under compressive machines and also slump flow test.

Review on the Australian position in green power generation

The Australian Department of the Environment and Energy stated [5] that Australia is committed to taking domestic and international action on climate change as the result of Paris agreement in Nov-Dec 2015. An ambitious target to reduce emissions by 26-28 per cent below 2005 levels by 2030 was set. By 2010, from the 30 coal-fired power plants operating in Australia, two-third of them are older than 20 years and only four employ clean coal technology [6]. CO2CRC as the authorised party facilitating the CO_2 capturing programs in Australia had stated in its 2017-18 report about the progress of 3 major projects in Australia. These projects are investigating the applicability of advanced membrane and solvent technologies on Vales

Point and Latrobe Valley. The innovation of new absorbents with enhanced kinetics by ion-exchange has also been reported[7]. A summary of the Australian CCS projects is provided in table 1 below:

	Project name	State	Estimated operation date	Capture facility	Capture type	Transport type	Storage type	CO_2 storage rate	Status
1	Lassie (D)	Vic	2015	-	-	Pipeline	Geological	>1 Mt.pa	Identification
2	FuturGas	SA	2017	Coal to liquid (Producing diesel and naphta / power / sulphur)	Pre-combustion	80-200 km pipeline	Geological (saline aquifer and/or depleted oil/gas field)	1.6 Mt.pa	Identification
3	ZeroGen	QL	2015	400 MW IGCC (coal) power plant	Pre-combustion	100 km pipeline	Geological (Saline aquifer)	2 Mt.pa	Evaluation
4	Browse LNG	WA	2015	LNG plant (gas processing)	NG processing	Pipeline	Geological (Saline aquifer and/or depleted oil/gas field)	3 Mt.pa	Evaluation
5	Wandoan Power (D)	QL	2015	400 MW net IGCC (coal) power plant	Pre combustion	200 km pipeline	Geological or beneficial reuse (EOR)	2.5 Mt.pa	Evaluation
6	Coolimba	WA	Not specified	2x200MW or 3x150MW coal fired CFB power plant	Post-combustion	20-80 km pipeline	Geological (depleted oil/gas field)	3 Mt.pa	Evaluation
7	Gorgon project	WA	2015	LNG plant (gas processing)	NG processing	Pipeline Geological (Saline aquifer) 3.4 Mt.pa	Geological (saline aquifer)	3.4 Mt.pa	Define

Table 1 Status of CCS projects in Australia (Source: global CCS institute, 2009)

Based on the definition made by the Global CCS Institute, a large-scale commercial CCS project is capable of storing 1Mt.pa or greater of CO_2 gas.

There are currently 22 active coal powered electricity plants in the four major states of Australia with a total maximum capacity of 24,004 MWh[8-10].

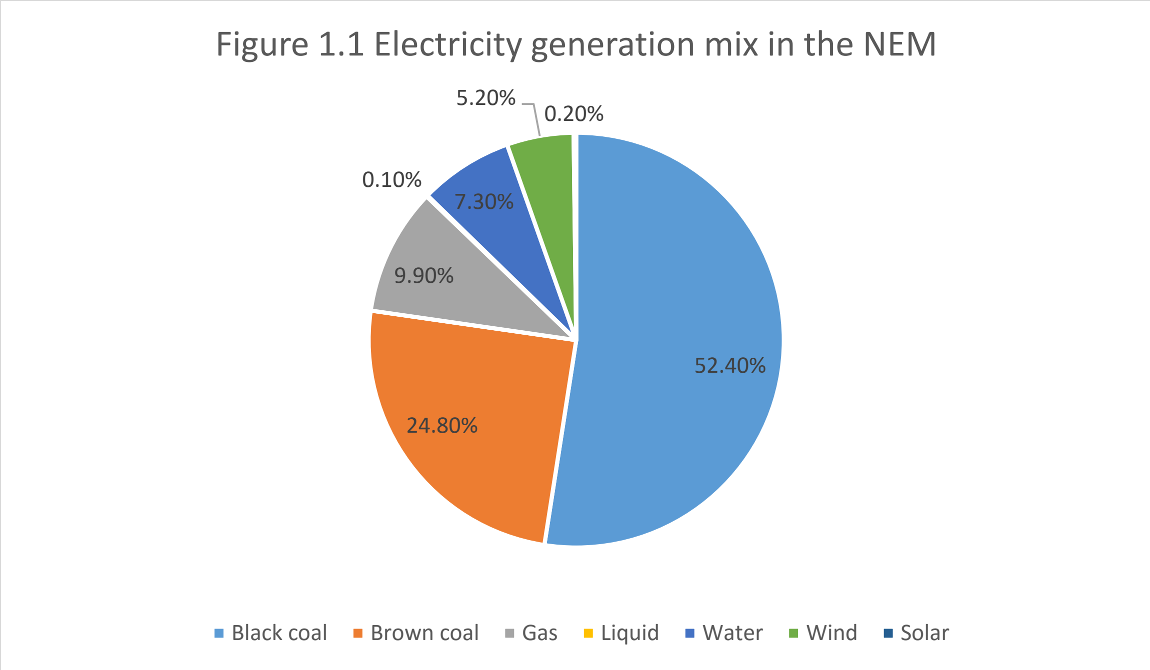
	Coal Burnt Power Station	State	Operating Company	Power Generation (MW)	Commissioned (Years)
1	Liddell	NSW	AGL Energy	**2,000**	1971
2	Vales Point B	NSW	owned and operated by *Sunset Power* International and trades as Delta Electricity	**1,320**	1978
3	Yallourn W	VIC	Energy Australia	**1,480**	1974
4	Gladstone	QLD	Rio Tinto, NRG Energy Inc, Southern Cross GPS Pty Ltd, Ryowa II GPS II Ltd, YKK GPS (Qld) Pty Ltd	**1,680**	1976
5	Gladstone QAL	QLD	–	**25**	–
6	Eraring	NSW	Origin Energy	**2,880**	1982
7	Bayswater	NSW	AGL Energy	**2,640**	1985
8	Tarong	QLD	Stanwell Corporation Limited (Stanwell)	**1,400**	1984 – 1986
9	Tarong North	QLD	Stanwell Corporation Limited (Stanwell)	**443**	2003
10	Loy yang A	VIC	AGL Energy	**2,210**	1984 – 1987
11	Loy yang B	VIC	Alinta Energy, CTFE	**1,026**	1993 – 1996
12	Callide B	QLD	CS Energy	**700**	1988

13	Callide C	QLD	CS Energy owns Calide C in a 50/50 joint venture with InterGen	**810**	2001
14	Stanwell	QLD	Stanwell Corporation Limited (Stanwell)	**1,460**	1993 – 1996
15	Mt Piper	NSW	Energy Australia	**1,400**	1993
16	Milmerran	QLD	InterGen	**851**	2002
17	Kogan Creek	QLD	CS Energy	**750**	2007
18	Collie	WA	Synergy	**340**	1999
19	Bluewaters 2	WA	Griffin Energy	**208**	2009
20	Bluewaters 1	WA	Griffin Energy	**208**	2009
21	Worsley (Alumina)	WA	BHP Billiton	**135**	2012
22	Yabulu	QLD	—	**38**	—

Table 2 List of Australia's coal burnt power stations

From the comparison of the data collected in tables above it can be concluded that only 1 out of 22 existing coal-power plants in Australia is equipped with carbon capturing techniques. The high cost associated with the transportation and storage are from the barriers.

In Australia, the National Electricity Market, NEM, and Western Australia’s South-West Interconnected System, SWIS, are the largest electricity suppliers. The NEM covers Australia's eastern and south-eastern coasts compromising five states: Queensland, New South Wales (including the Australian Capital Territory), South Australia, Victoria and Tasmania [8]. Currently, coal fired power plants (both brown and black coal) makes up 78 per cent of electricity generation across the NEM. This is followed by gas, compromising for 9.9 per cent. Figures 1.1 and 1.2 depict Australia's electricity generation mix.



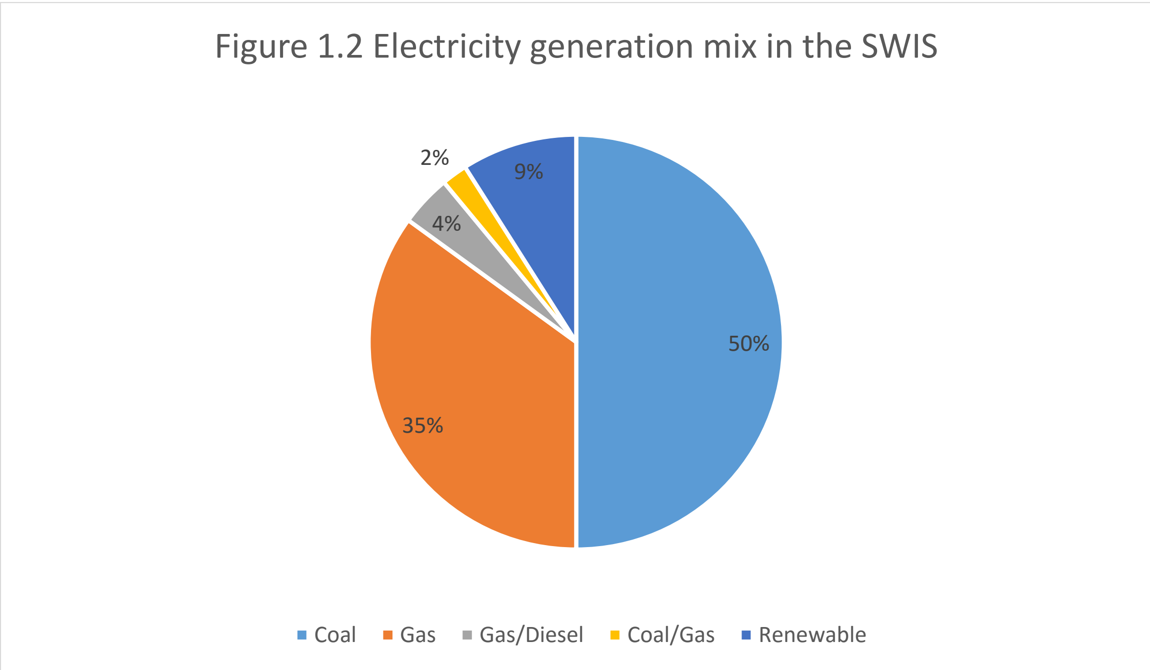


Figure 1 - Electricity generation mix in Australia

Estimates of Australia's greenhouse gas emission are produced by the Australian Department of Environment. Nearly half of all NSW emissions in 2013/2014 were from the stationary energy sector, primarily from public electricity production. Burning fossil fuels accounts for over 99% of emissions in the sector. Because of the low-cost of production and abundance of coal supplies the energy producers' tendency leans toward the use of coal powered plants. Coal combustion alone produces 51 million tonnes of emissions annually or nearly 39% of all

NSW greenhouse gas emissions [11, 12]. Another studies [13, 14] show that by considering the variation in the types of coal being used in power generation, combustion technologies and operating conditions, the CO_2 emission per unit of electricity is estimated to be in the range of 0.91 to 0.98 kg/kWh. A median 600 MWh coal-fired power plant emits 500 m^3/s of flue gas containing about 15% CO_2, totalling to about 11,000 tons of CO_2 emission per day. It was reported that brown coal combustion emits relatively higher amount of CO_2 compared to black coal.

There are three options to reduce total CO_2 emission into the atmosphere, i.e., to reduce energy intensity, to reduce carbon intensity, and to enhance the sequestration of CO_2. The first option is basically promoting more efficient use of energy. The second option, hoewever, requires a switch to using non-fossil fuels such as hydrogen and renewable energy. The third and the most promising method is known to be CO_2 capture and sequestration technologies at power plants [15]. Post-combustion capture, pre-combustion capture, and oxy-combustion are three methods recognized to be effective in this area[16]. Table 3 shows a comparison of positive and negative points of each of these three methods.

	Advantages	Disadvantages
Post-combustion	• Applicable to the majority of existing coal-fired power plants • Retrofit technology option	• Low CO_2 partial pressure resulting in significantly higher performance or circulation volume requirement for high capture level.
Pre-combustion	• Synthesis gas is concentrated in CO_2 resulting in high CO_2 pressure and reduction in compression costs/loads • More technologies are available for separation	• Applicable mainly to new plants, a few gasification plants are currently in operation. • The commercial application is often costly. • Extensive supporting system required.
Oxy-combustion	• Highest concentration of CO_2 in the flue gas	• Cooled CO_2 recycle required to maintain temperatures within limits of combustor materials

	• Retrofit and repowering technology options	• Low process efficiency caused by the heat generation

Table 3 Advantages and disadvantages of different CO2 capture approaches[16]

Post combustion carbon capturing

As the name indicates, the post combustion methods are facilitating the process of CO_2 capture from the flue gas after the fuel had been burned for energy generation purposes. A typical procedure in this process is as demonstrated in figure 2. The amine treatment of the flue gas is a widely acceptable method in the post combustion capturing method. MEA commercial absorption process constitutes of the removal of the CO_2 from the flue gas in an absorber. MEA reacts with CO_2 in the gas stream to form MEA carbamate. The CO_2-rich MEA solution is then sent to a stripper where it is reheated in order to release the CO_2. The CO_2-free MEA is recycled afterward[17].

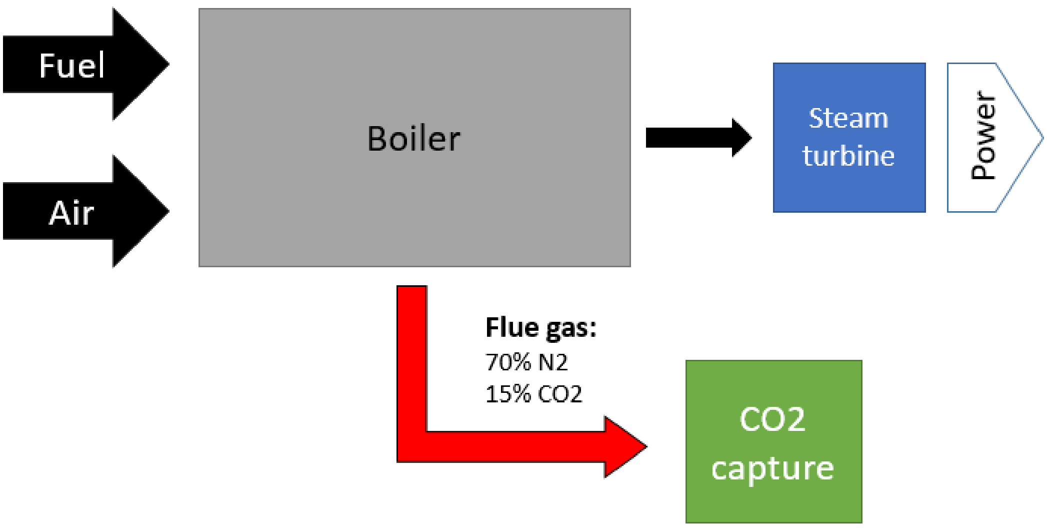


Figure 2 - Post combustion carbon capture procedure

Other solvents are also applicable for this process such as hot potassium carbonate, chilled ammonia and ionic liquids[2]. Monoethanolamine is by far the most well-known amine-based absorbent due to its high chemical reactivity and low cost of production. There are number of issues incorporated with the use of MEA in carbon capturing. High enthalpy of reaction, low absorption capacity, oxidative behaviour followed by corrosion and thermal degradation.

The solvent chemistry becomes important once it's realised that the circulation flow rate required for capturing a given amount of CO_2 by having a higher CO_2 absorption capacity. The kinetics data derived from the chemical reactions also allow the determination of the size of the absorber or desorber columns. One of the critical factors to be considered in the design process of absorber or in the selection process of the solvent is the equilibrium solubility of CO_2 in the solvent as a function of temperature and pressure shown in Figure 3. The estimation of heat energy required in the post combustion process can also be obtained from the solubility data. Henni et al. reported that the CO_2 solubility increases in amine-based solvent exposed to higher pressure[18].

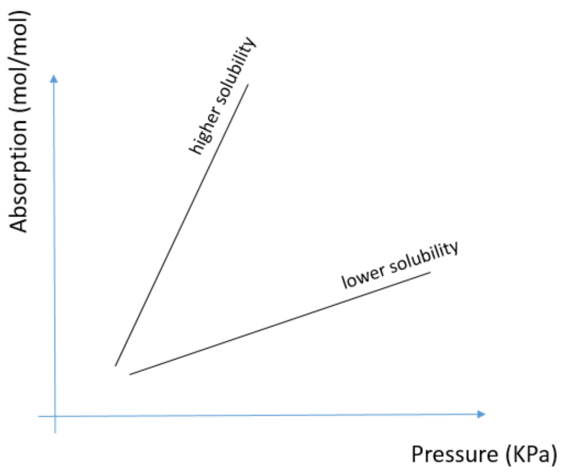


Figure 3 - Correlation of CO2 solubility in amine-based solvents with pressure

Monoethanolamine overall reaction with CO2 develops as followed in equation 1 [2]:

$2\ MEA + CO_2 \rightarrow MEA\text{-}COO^- + MEAH^+$

$CO_{2(g)} + H_2O_{(l)} \leftrightarrow H_2CO_{3(l)}$

$MEA + CO_2 + H_2O \leftrightarrow MEA\text{-}H^+\text{-}COO^-$ (zwitterion) $+ H_2O$

$MEA\text{-}H^+\text{-}COO^-$ (zwitterion) $+ H_2O \leftrightarrow MEA\text{-}COO^-$ (carbamate) $+ H_3O^+$

$H_3O^+ + MEA \leftrightarrow MEAH^+ + H_2O$

$H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H_3O^+$

$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$

$MEA\text{-}COO^- + H_2O \leftrightarrow HCO_3^- + MEA$

Equation 1 Chemical reaction of Monoethanolamine with CO2 gas.

Since the conventional amine technologies are costly, energy intensive and if implemented would result in large increase in the cost of producing electricity, it is suggested to employ the membrane systems to enhance the efficiency of the conventional MEA (Monoethanolamine) capturing technologies[12]. It has also been reported that the capture of the 90% of the CO2 in flue gas requires 30% of the power generated by the plant which adds up a cost of $40-100 for a ton of carbon dioxide. The monoethanolamine absorption would increase the cost of electricity production by 70%. [19, 20]. Another study ran by Paul Feron et al. [21] proposes a metal mediated electrochemical process to harvest the CO_2 absorption enthalpy into electric power to compensate the capture energy consumption. It was reported by the same author that *the energy output of 4.1kJ/mol CO_2 was achieved experimentally at the studied conditions, resulting in an enthalpy-to-electricity conversion efficiency of 6.4%.* Modularity and the compactness of the membrane units are from the benefits of utilizing membranes as the sequestration method. Membrane technology is a non-dispersive contacting system that the flue gas does not interact chemically with the membrane. Membrane systems brings 30 times more interfacial area than the liquid phase gas absorption methods [22]. Compared to the issues encountered with the use of liquid absorption such as corrosion and foaming, utilization of membrane technology in post combustion carbon capture, benefits the whole process by cost savings reported as 38-42%, equipment weight reduction of 34-40%, as few significant advantageous reported by Falk-Pedersen et al[23]. One of the limitation to the application of membranes is the capital and energy cost of pressure equipment. Sufficient level of pressure plays an important role in the membrane capturing process as it affects the flue gas flow rate.

Pre-combustion carbon capturing

The pre-combustion methods are chemical procedures involved in the steps before the fossil fuel combustion. These are usually chemical gasification of the input coal aiming to lower the amount of CO_2 emission after the combustion. In this process as pictured in Figure 4, coal is combined with oxygen to produce a gas made up of carbon monoxide and hydrogen (Syngas). By adding water to the syngas, CO_2 is produced and captured while the hydrogen is burned to generate power. Pre-combustion capture is potentially less expensive than post-combustion capture [15, 20].

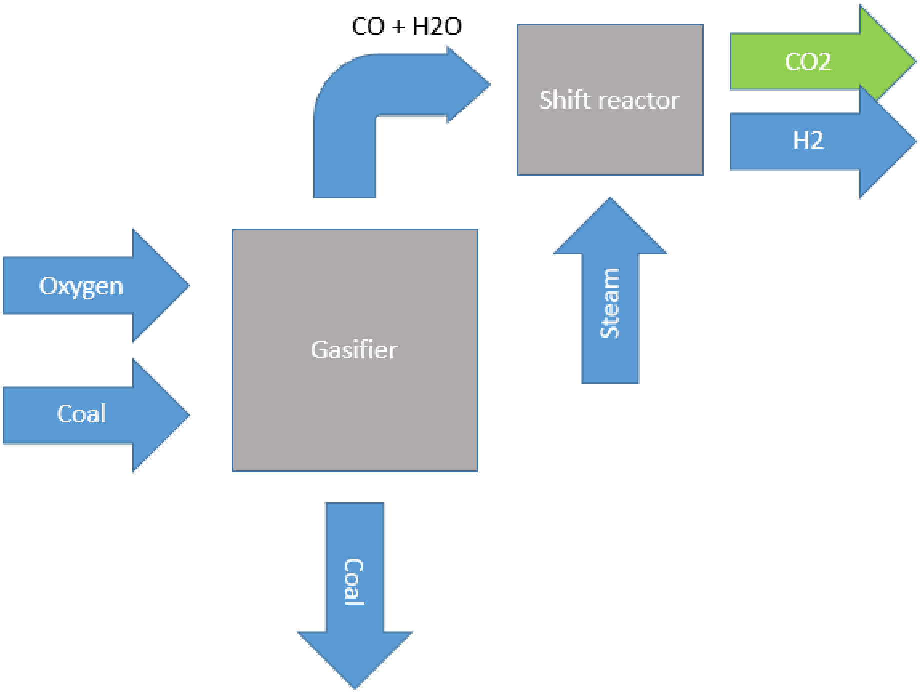


Figure 4 - Pre combustion carbon capture procedure

Scientist believe that the utilization of solid sorbents may be more efficient in some cases as compared with the efficiency of liquid phase sorbents. In the pre-combustion CO_2 capturing practices in the coal-fired power plants solid adsorbents are being used such as zeolites, activated carbon, calcium oxides, hydrotalcites, supported amines and metal-organic framework materials. Amongst the spectrum of solid molecular sieves, activated carbon (AC) and aluminosilicate zeolites show considerable adsorption capacity. It was reported by S. Garcia et al. that in lower CO_2 partial pressure, the capturing capacity of AC is lower than zeolite based sorbents. However, this ratio reverses once the partial pressure increases. It became of the interest of researchers to understand the correlation of pressure and temperature with the capturing capacity output. Experimental data revealed that the effect of temperature is negligible compared to pressure. The optimum CO_2 partial pressure is stated to be 300 kPa (Total pressure to be 1500 kPa) at the temperature of 25°C in order to obtain the maximum capturing capacity of 3.96 mol/ kg adsorbent[24]. Another study done by Trevor C Drage et al., however, shows that maximum adsorption capacity of activated carbon reached to up to 12 mol/kg in a total pressure of 4,000 kPa[25], which brings lack of consistency in the results obtained from the S Garcia's research. The inconsistency in the reported results, in fact, indicates the immaturity of the pre-combustion carbon capturing technique which makes the adoption of such technology unlikely compared to other methods. Chungsying Lu et al. in another paper compared the adsorption level of carbon nanotube, zeolite, and granular activated carbon in the same order respectively from high to low[26].

Oxyfuel-combustion carbon capturing

Such technology separates the oxygen from the air prior to combustion and produces a nearly sequestration-ready CO_2 effluent. In this case as pictured in Figure 5, the coal is burned exposed to a nearly pure oxygen and emits a high concentration of CO_2 which is almost ready for sequestration. The by-product of this process contains a high volume of H_2O which is cooled down in order to separate the CO_2 properly.

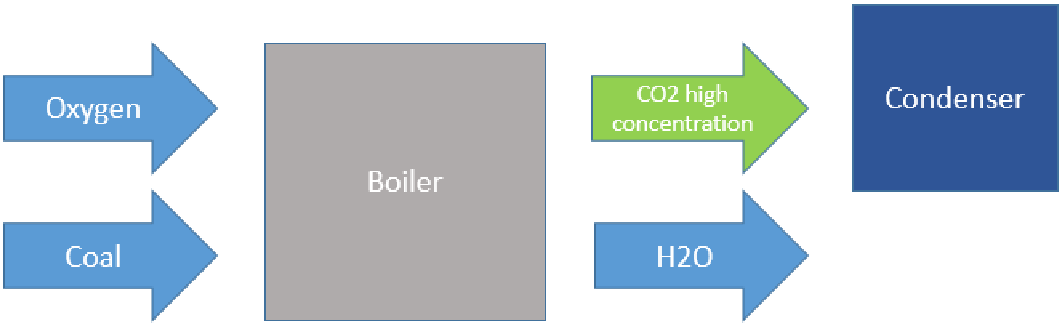


Figure 5 Oxy-fuel carbon capturing method procedure

This study aims to address the following research questions:

- What are the current coal power plants operating in NSW? What CO_2 capturing method do they utilize?

  To understand the answer to this question, governmental documents and literature exist in this field had been extensively reviewed.
- What barriers exists in the implementation of CO_2 capturing methods?

  Literature review would reveal the answer to this question.
- What are the alternatives to ease the CO_2 storage methods?

  An innovative idea of the use of the by-products of post-combustion capturing technique had been explained and tested in the laboratory.
- How does the construction industry could be a place to utilize both CO_2 capture and storage?

  Laboratory experimental tests had shown a set of promising results for the use of these by-products in concrete production. Survey results also on the other hand had shown the market capacity to embrace such new approach.

Methodology

This paper, first identifies the plans and programs for CO_2 capturing and storage in Australia as a whole. Name and the status of the projects are outlined. This was done by collecting scattered data from governmental documents and scientific literature available on the public domain in order to provide an extensive report on the current status of operating coal power plants in Australia. Executive summary reports from the Australian Government Department of Environment and Energy were combined with the data published by Global CCS Institute. The review on literature in addition to previous studies on the use of recycled aggregate reveals that one of the environmental approaches in construction is the use of recycled aggregate in concrete. Combined with the CO2 capturing analogy a new chemical admixture had been produced that enhances the properties of concrete made with recycled aggregate. The results and explanation of experimental laboratory test on the applicability of a new type of concrete chemical admixture were introduced as followed. The proposed product consumes the by-product of post combustion capturing method as part of the synthesis process. Survey results obtained from the site visits to recycling plants and concrete batching plants were provided in order to match the supply and demand of recycled aggregate and market capitalization matters.

CO_2 capture from cement industry

After power generation cement is known as to be the second largest anthropogenic emission source, contributing approximately 7% of global CO_2 emissions. It is stated that the large cement manufacturers on average have a higher RoE (Return on Equity) and lower debt ratio, therefore a higher discount rate should be considered for the cost analysis compared to power plants. This is while the International Energy Agency (IEA) estimates that the global decarbonisation of cement sector costs AUD$350-840 billion. Global cement production accounts for approximately 9.6EJ of energy consumption and 1.9 Gt CO2 emissions per year [27]. Cement related CO2 emissions originate from a number of sources in the production line where 50% is associated with the process of converting limestone (CaCO3) into calcium oxide (CaO) in the midst of the formation of so called clinker. 40% of the CO2 emission in the cement production results from the combustion of fuel in the kiln and the remaining 10% roots from the transportation and electricity use in other parts of the process[28]. A study conducted in 2011 analysing the post combustion CO2 capturing from a coal power plant in Australia revealed a AUD$68/tonne cost associated with the process. This is comparable with the cost associated with the CO2 capture from a cement plant in Canada reported as AUD$49/tonne that is %27 cheaper [29].

Application of the by-products of the post-combustion methods in construction industry – CO_2 storage

One of the challenges facing the capturing technologies returns to the storage issues. In other words, the sequestration of CO_2 from the flue gas if successfully and commercially adopted via the three methods previously discussed, follows with the question "How to consume the captured CO_2 now?". Storage technologies introduce an alternative to safely consume the CO_2 in a manner that the highly pressurized gas being entrapped under the layers of the ground facilitating the oil and gas extraction processes (Use in petroleum industry). But, due to the geotechnical difficulties encountered with the implementation of this storage technique, it is unlikely to adopt such in a broader scale. Monoethanolamine is one of the widely used substances in the post-combustion technique of CO_2 capture. The experimental studies done during the terms of this research show that the by-product of such a process once had been used in concrete can enhance the mechanical properties of concrete made by recycled aggregate.

From the benefits of using such chemical admixture is the acid treatment of recycled aggregates during the mixing process. Interfacial Transitional Zone (ITZ) is known as the main factor in the low quality of recycled aggregate as the old cement mortar attached to the core degrades the overall performance of the recycled concrete [30-32]. The high recorded pH of 11 for the proposed concrete chemical admixture, in fact, facilitates the acid treatment of recycled aggregate once used. On the other side, the conventional CO_2 Concrete technology proposed by Tam et al. [33] encompasses the CO_2 molecules in a physical interlock with a low absorption rates using a pressure chamber. The current chemical admixture increases the absorption rate to up to 90% by activating the CO_2 gas chemically upon the reaction with other substances.

The other challenge that comes with the use of recycled aggregate in concrete is the high water absorption of such aggregate. This property affects the workability of concrete in a significant way which makes an environmental type of concrete as such unfavourable to the eyes of contractors [34-36]. For the commercial use of recycled aggregate as in ready-mix concrete produced at batching plants, the delivery time of the truck mixers are limited to less than 90 minutes. Lower water content available in the mix for the hydration reaction of cement means that the setting time of concrete would decreases consequently as well. This would basically mean that concrete batching plants will be having a smaller area for service affecting the number of customers and the profit margin as well. The newly proposed concrete admixture had shown a rheological enhancement on the fresh state of concrete.

The following results in table 5 were obtained during the experimental tests.

Dosage wt% of cement[1]	7days Compressive strength (MPa)	Slump table flow [37]
3%	25.6	41
5%	36	46
7%	31	52

Table 1 Properties of concrete made by the addition of the proposed chemical admixture.

In terms of the microstructure of concrete, the interface between the recycled aggregate and cement mortar plays a crucial role on the compressive strength. Also known as interfacial transition zone (ITZ), this zone corresponds to the binding and the interlocking of cement paste and aggregate. In concrete made of recycled aggregate, the ITZ is usually weak due to the attachment of the old cracked mortar on the surface of the recycled aggregate [38-40]. Several studies show that the use of low concentrated acid to maximize the adherence between recycled aggregate and the cement paste is in fact an effective method which ultimately leads to enhancement of the mechanical properties of concrete. One of these methods, for example, recycled aggregate is soaked in three different types of acid, namely, hydrochloric acid (HCl), sulfuric acid and phosphoric acid at a molarity of 0.1 M for 24 hours. In general, the treatment significantly reduces the water absorption of recycled aggregate by 7.27–12.17%. As a result, the compressive strength, flexural strength, and elastic modulus of the treated recycled aggregate are improved compared with those of untreated recycled aggregate[41-43].

[1] Concrete chemical admixtures are usually being added to the mix with the mentioned ratios.

Figure 6 - Footage from the effects of newly proposed chemical admixture on the fresh state properties of concrete made by recycled aggregate.

In accordance with data gathered from Australian natural and recycled aggregate market a ton of 10mm and 20mm recycled aggregate price is roughly $92 however the same size natural aggregates cost $192, indicating the direct effect on the final concrete product. Furthermore, considering the significant reduction in numbers of transportation cycling between the construction/demolition site and the recycling plant, it can be resulted the reduction in labour wages and fuel cost not to mention the depreciation rate of civil machineries. The same research on the supply of recycled aggregate in Sydney metropolitan showed a production capacity of 20,000 tons of recycled aggregate per month[44].

Based on our survey all of the concrete batching plants refuse to use recycled aggregate in concrete production. Variety of roots has been asked for the reason behind not using recycled aggregate in concrete including:

- Lack of experienced staff in this field
- Lack of demand for recycled concrete
- Lack of supply of recycled aggregate
- Technical barriers

The first reason comes out to be the technical difficulties of using recycled aggregate in concrete. It has been stated that the recycled concrete drops the slump extensively in less than 30 minutes. The average delivery time is 45 minutes. This time difference leads the workability of the fresh concrete to be low enough to discourage concrete distributors and concrete workers using such aggregates in concrete. The low workability of recycled concrete is due to the high porosity of recycled aggregate. Before the batch being delivered to the construction site, a considerable amount of water required for the hydration chemical reaction, absorbed by the recycled aggregate. Studies showed that a process named carbon conditioning recycled aggregate will cause the voids inside the recycled aggregate to get filled by other chemical components[33], leading to a total low porosity of recycled aggregate and, as a result, higher workability of concrete made by carbon conditioned recycled aggregate .

Having all the data gathered, the main recycled aggregate consumer across the construction industry in Sydney is the road construction sector. Still, it has been observed and stated that some construction and demolition waste recycling plants have a relatively long non-productive period throughout a year. This indicates that even though the first recycled aggregate consumer is the road construction section, the supply of recycled aggregate is much higher than the existing demand.

Taking the 240,000 tons as an annual production capacity of the metropolitan and the recommended mass portion of CO_2 agent to aggregate as 1/60, the gross annual demand of 4,000 tons of the proposed chemical additive would be resulted. Another financial benefit that the mass promotion of such product claims is the cost savings associated with the elimination of heat energy requirement for the separation of CO_2 from the rich Monoethanolamine outlet from the absorption tower. Simply explained, the CO_2 rich Monoethanolamine could be transported directly to the concrete admixture factory for the further uses.

Acknowledgement

This research could not be accomplished by the facilitation of Western Sydney University technical staff members, supervisors and fellow academics. Special thank goes to the Graduate Research School of Western Sydney University for regulating and providing the necessaries required for the accomplishments of this paper. Western Sydney University library staff had fantastic contribution in the data collection procedure. The contribution of Institute of Construction Materials (ICONSMAT) had also shed light on the alignment of this research.

Conclusion

The high cost associated with the transportation of the captured CO_2, which is mainly accomplished by pipelining, low efficiency in the adsorption/absorption rate, immaturity of the industry, etc. all together increases the risk of investment in the CCS projects. In order to facilitate the issues encountered with the adoption of CCS techniques and ease the approach toward zero emission goal, this study proposed an experimented concrete chemical admixture which is useful in the enhancement of properties of concrete made of recycled aggregate.

Results of the slump flow and 7 days compressive tests show a workable high performance recycled concrete. The proposed "Green concrete chemical admixture" could be seen as a solution for storage issues brought by CCS projects and also at the same time enhances the properties of recycled concrete. The barriers for a wider general use of recycled aggregate in concrete had been explained to clarify the current status of market.

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Construction productivity indices in socialism compared with capitalism

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Abstract

Uncertainties in technology and budgets in dynamic industries such as construction leads the participants in an ambiguity in regards to assessing the success of the project. The construction community attempt to develop a comprehensive framework providing a solution to assess the succession where many believe that completion of the project on time and under budget are not the only main criteria to evaluate whether a project was achieved satisfactory results. In this context, this paper seeks to present a recent compatible set of key performance indicators (KPI) based on the current existing technologies available to contractors and builders. The effect of social practices worldwide including socialism and capitalism on wealth generation had been discussed and the labours' productivity in each type of societies had been assessed based on the data collected from the questionnaires. Analytical Hierarchy Process was conducted to prioritise the KPIs in each societal context.

Keywords:

Construction productivity; Automation; KPI; AHP

Introduction

It is usually assumed that the construction productivity is equivalent to labors' productivity, however, in the modern complex construction practices the criteria in which the productivity must be assessed against with, should demonstrate the broader term of this particular industry when it's compared to labors' productivity. These are project schedule, constructability, quality of design, completion date, project budget, equipment design, materials quality, legal and regulatory structures, training and educational programs. It has been stated in many articles published that the construction productivity is declining in the past decades. Physical capital, educational attainment and most importantly the social infrastructure/school in which the project is based on, geographically and management wise, are the contributing factors determined to be the reasons-why. This study investigates the effect of socialism and capitalism as the two major dominant school of thoughts on the construction productivity level. From the perspective of project management as a whole, productivity can be measured by the level of innovation in an industry i.e. the more innovative practices exist in an industry; the more productivity it attains. Another stiffening fact that shows the low productivity level in the construction sector is the total capital expenditure in construction R&D. Number of patent grants is a viable measure to understand the level of expenditure on and thus appreciation of innovation in a country. An efficient risk management is another indicator to identify the productivity of the construction industry. Due to the complex nature of construction activities caused by the large number of uncertainties exist in the projects, the associated risk with the succession is relatively high compared to other industries[1-6].

Productivity is widely accepted to be defined as the fraction of output to input. The challenge usually is the authentication of outputs as the inputs are often have a higher certainty level as opposed to outputs where the effects appear later in the future operation stage of the projects. However, more comprehensive analysis takes into account the completion time, human resources satisfaction rate, the rate of return of the project, environmental impacts, and etc.

Participants' way of thinking in evaluating the origins of wealth may vary based on the society they live in. For instance, in middle-east where the socialism is the acceptable driving factor of economy and politics, individuals' profit gained by the completion of the project is not appreciated as it is in capitalism. However, capitalist does not see a project viable unless it yields financial profit. From that, construction managers are ought to understand the society in which the construction is located and the ethnicity of the labours for compensation matters. The labours remuneration does perhaps have a direct relation with the productivity of labours as it increases.

Socialism as the dominant driving factor in the valuation of wealth in Middle-east appreciates factors such as philanthropy, public interest, self-devotion. On definition, socialism is a populist economic and political system based on public ownership of means of production. Machinery, tools, and factories used to produce goods aim to directly satisfy human needs in this economic way of thinking. It is believed in socialism context that shared ownership of resources and central planning provide a more equal distribution of goods and services. Socialist ideals include production for use rather than for profit. An equitable distribution of wealth and material resources among all people basically leads to the elimination of completion in the market and encourages the free access to goods and services.

Capitalism, on the other side, is an economic system where the goods and services are owned by the private sectors. The market follows the law of supply and demand which leads to empowering of competitiveness. The high end of capitalism provides free market in which private individuals are completely unrestrained in determining where to invest and operating without checks or controls. The goal of capitalist is to increase profit. It is known that a company must embrace innovation by introducing new efficient goods and services providing higher value proposition throughout its life in order to remains competent in the market and earn profit [7, 8].

For the purpose of this study, 4 criteria were selected known as innovation, automation. Environmental impacts, shareholders' satisfaction to be compared in the socialist and capitalist point of view.

Methodology

The four criteria (A.K.A. Key Performance Indicators) selected for this study known as innovation, automation, environmental impacts, and shareholders' satisfaction are firstly defined with more focus on innovation. Analytical Hierarchy Process (AHP) then had been described which is going to be used for prioritizing the importance of each of the four factors in capitalism and socialism. A short online survey including 7 questions had been conducted to collect the opinions of construction industry participants in the field of this study. Next, AHP had been run on the survey results collected. An analysis of the AHP model is then being provided in the Results and Discussion section.

Innovation

As stated by Hardie and Newell [9], "Creativity only flourishes in an atmosphere of openness and overly cautious risk aversion can stifle the potential of innovative suggestions". In this study in order to quantify the level of productivity in socialist and capitalist economies, the level of innovation in countries ruled by socialists had been compared to those ruled by capitalist school of thought. Data were collected from the World Intellectual Property Organization (WIPO) since 2000 until 2017 based on the total counts applicant's origin and taking the indicator as to be the number of patent grants by technology. Australia, United Kingdom and Canada were selected as the examples of economies run by capitalist theories. The top two countries run based on the socialist school of thinking are China and Russia, however, since the population of these two countries together adds up to more than 1.4 billion people more than the sum of population of UK, Australia and Canada the output data would become incomparable. In fact, the mathematical possibility of patent registration grows by higher population as there would be more chance of people becoming interested in innovation. Based on this, Iran, Iraq and Afghanistan had been selected as the examples of socialist economies in this study. This concludes the sum of population capitalist sample as 127.6 million people and socialist countries to 122.74 million. The field of technologies in which the analysis is conducted on are materials and metallurgy, environmental technologies and civil engineering.

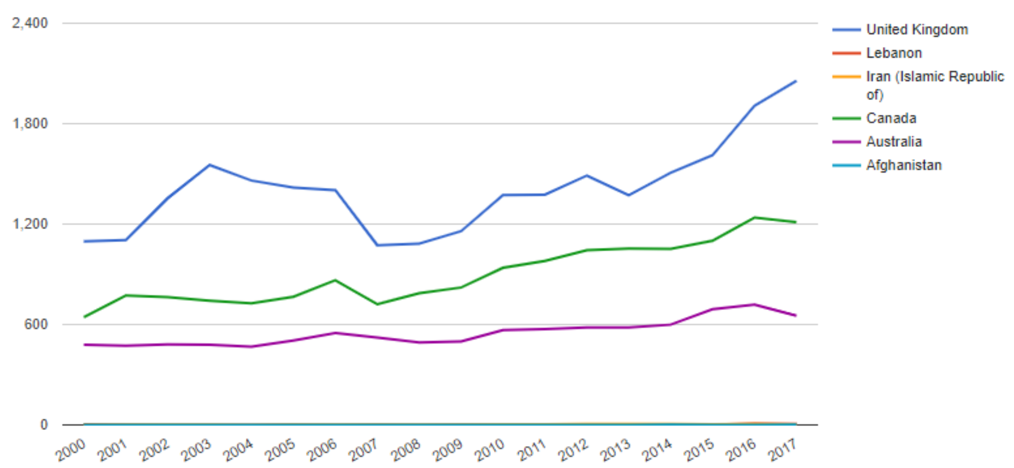

Figure 2 Number of patent grants

Figure 1 shows the difference in the rate of innovation in capitalism and socialism. Iran and Portugal are ranked drastically below the UK and Australia. Taken the level of innovation as an indicator of productivity, it can be stated that the construction productivity in a sample of 90 million people in socialist economies are low compared to capitalist economy. The steady state of growth in innovation in Australia compared to UK is another remarkable information obtained from figure 1. This happens while the population growth in Australia is recorded as 22.1% since 2000 from 19.15 million people to 24.6 million people. Positive growth in population and the steady state of innovation shows a weak point in initiating the R&D incentives in the Australian construction industry.

Table 2 Population demographic in socialist economies

Socialist economies selected			
	Population as per 2018	Population as per 2000	Growth rate
Iran	81.16	66.13	18.5%
Lebanon	6.08	3.72	38.8%
Afghanistan	35.5	25.94	26.9%
Total	122.74	95.79	21.95%

Table 3 Population demographics in capitalist economies

Capitalist economies selected			
	Population as per 2018	Population as per 2000	Growth rate
Australia	24.6	19.15	22.1%
Canada	37.06	30.69	17.2%
UK	66	58.89	10.7%
Total	127.6	108.73	14.8%

From the data provided in tables 1 and 2 and taking the direct positive correlation of population growth with economic growth [10, 11] into account, it was anticipated that innovation should be promoted in a higher scale in countries with higher a population rate of growth. Although middle-eastern countries show a considerably higher rate of growth in population, the number of patent grants is drastically lower compared to capitalist economies. This strengthens the hypothesis of the negative effect of socialism way of thinking on the level of productivity in middle-east as compared to western countries.

Perhaps, the risk associated with the success of an innovative idea is much higher than implementing old-fashioned technologies. This can be one of the main factors that managers in socialist economies tend to avoid accelerating the innovative ideas and technologies. At the same time in capitalist economy, the cash flow rate and/or the high liquidity of a company is seen as a positive sign and shows the dynamic behaviour of the company where investors appreciate. The appreciation of dynamic cash flow structure of companies in capitalism indicates the acceptance of high risk associated in these economies which opens space for innovation and thus a higher productivity rate.

Also briefly, just to indicate the importance of Public-Private Partnership in the success of inventions, a study conducted by Rothwell and Zegveld in 1981 conclude that the number of innovative approaches and technologies achieved by public procurement contracts without direct R&D subsidises are larger than the R&D subsidies[12]. Public private partnership (PP are long-term agreements between public and private entities that foster objectives of a construction project.

Automation

Automation on the other hand, enhances the accuracy of the tasks being done as well as the speed in which the project forwards. Autonomous construction machineries are safer in terms of workers' health condition as there would be less human interaction in case robotics being implemented in construction projects. Although construction industry suffers from its high labour intensity, the emergence of self-driving cars equipped with artificial intelligence can be a promising approach towards a safer and more productive practices. Perhaps, Building Information Management (BIM)In systems had up-scaled significantly in the context of software development, still, the integration of BIM with construction machineries remains almost unattended. It is anticipated that up to 2.7 million US construction workers compromising almost half of the total workforce in the same sector would be replaced by robots by 2057. If true, sever social consequences arrive such as high unemployment rate, economic depression, increase in homelessness, etc. In fact, the driven factor for such consequences of automation returns to the idea that the business owners welcome labour cost savings for the promise of higher productivity, which is one of the basic rules in capitalism [13-16].

A comparison between the construction and the automobile industries shown in figure 2 conducted in 2008 in Europe reveals the growing level of productivity in automobile industry as oppose to the construction where the productivity level keeps constant if not declining [17].

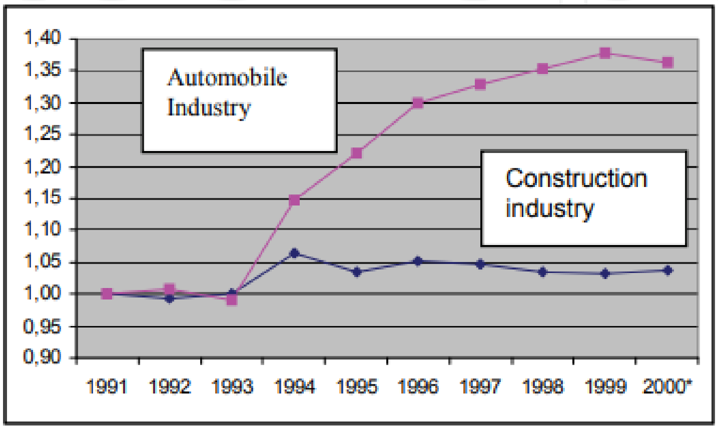

Figure 3 Productivity level in construction compared to automobile industry

It was explained that this productivity gap is due to the differences in the utilization of Computer Integrated Manufacturing (CIM) in both industries[17]. Some of the key advancements in the automation of construction machineries are GPS-based tracking, sensor-based navigation either by the method of laser detection, or video analysis technologies, internet of things (IoT) which is a protocol of machine-to-machine communication to increase connection of devices and objects over the internet.

Environmental impacts

It's been stated that the productivity level increases when motivation for accomplishing the tasks would be high. The motivation, in fact, derives from the perception of wealth in the society. Baker et al. [18] defines project success as: "If the project meets the technical performance specifications and/or mission to be performed and if there is a high level of satisfaction concerning the project outcome among key people in the parent organization, key people in the client organization, key people in the project team and key users or clients of the project effort, the project is considered an overall success". As an example of a wealth perception, the recycling incentives in Australia is highly valued with a high 60% recycling rate of the total of 64 million tons of waste produced in 2014-2015. The quantity of material recycled in Australia increased significantly. - Recycling increased by 30% over the period from 27 to 35 Mt or 1.4% per capita per year. Waste policies and programs have been established at all levels of Australian governments— Commonwealth, state, territory and local. Policy and legislative responsibility for waste rests with the states and territories, and policy at this level has the greatest influence on waste management [19]. Many other similar examples exist across the countries that are appreciating the environmental restoration as well. While environmental conservation is becoming one of the attractive topics since last decades one of the most important world-wide ecological objectives is the reduction of CO_2 emission. Indirectly, the construction industry is one of the principle sources of these emissions. Consider the enormous furnaces used in steel manufacture, cement factories, ceramics industry, or transport. These all include processes which invest energy in the production of construction materials. It has been calculated that in order to produce a ton of concrete 4GJ of energy is required [20].

Shareholders' satisfaction

Shareholders by dentition refers to the group of participant in a project that without their support the organization would cease to exist[21]. Redefining the customers in the complex environment of construction sector, builders, contractors, residents, educators are forming a few of the roles exist in this ecology. In the capitalist school of thought, as the market operates in an open competition environment, the businesses, and in this case construction sector, must enhance the service quality in order to achieve a higher customer satisfaction. Customer satisfaction, indeed, ensures the survival of sectors in a competitive environment[22]. On the other side where socialism rules, as the management is often centralized (similar to the idea of monopoly vs. oligopoly)c, the managers and decision makers must ensure the satisfaction of participants in order to ease the living of the customers.

Analytic Hierarchy Process

For ranking the importance of each criterion defined above, analytic hierarchy process was chosen as the method for this study. Due to high complexity of construction projects, prioritizing the effect of productivity benchmarks becomes one of the challenges facing managers. The Analytic Hierarchy Process (AHP) is method for relative measurement of intangible criteria. The scale of priorities in this method is a result of pairwise comparison. AHP, in other words, is a tool for multiple criteria decision-making. In order to proceed with this method, a set of criteria must be firstly outlined those that affect the productivity level in construction. From the literature these criteria are taken as innovation, automation, environmental impact, and shareholders' satisfaction. The result of pairwise matrix is usually denoted in a matrix as below:

$$\text{Pairwise comparison matrix} = \begin{pmatrix} w1/w1 & w1/w2 & w1/w3 & w1/w3 \\ w2/w1 & w2/w2 & w2/w3 & w2/w4 \\ w3/w1 & w3/w2 & w3/w3 & w3/w4 \\ w4/w1 & w4/w2 & w4/w3 & w4/w4 \end{pmatrix}$$

Where the diagonal arrays are always equal 1. The pairwise comparison matrix is then normalized in order to create a unified weighted score sheet that can ease the prioritizing. The number of comparisons to be made can be derived from the famous equation $\frac{n^2-n}{2}$ [23-26]. Consistency ratio is a measure to evaluate the level of accuracy of the inputs given by the survey participants. Simply explaining, this ratio indicates to what degree of randomness the survey had been completed. The procedure in checking the consistency of the inputs are as followed:

1. Determination of a weight sums vector, W_s

   $\{W_s\}=[C]\{W\}$

2. Finding the consistency vector

$\{W_s\} = [C]\{W\}$

Dot product $\{Consis\}=\{W_s\}.\{\frac{1}{W}\}$

3. Determining the average of the elements of {Consis} called λ also known as eigenvalue
4. Determining the consistency index, CI

$$CI = \frac{(\lambda - n)}{(n-1)}$$

Where n is the number of criteria

If CI results 0.00 (in the perfect world), the pairwise comparison would be perfectly consistent.

5. Searching for Random Index, RI in the table below based on the number of criteria given by Saaty in 1987 [27]:

Table 4 Derivation of random index

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

6. Calculating the Consistency Ratio, CR

$$CR = \frac{CI}{RI}$$

If CR < 0.1, the rankings are consistent

If CR ≥ 0.1, the comparisons should be recalculated

AHP allows some small inconsistency in judgement. Inputs are subjective opinions and outputs are ratio scales and consistency index. Briefly explained the steps involved with AHP method are as followed:

1. Define objective

2. Structure elements in criteria, sub-criteria, alternatives etc.
3. Make a pairwise comparison of elements in each group
4. Calculate weighting and consistency ration
5. Evaluate alternatives in accordance with weightings

[23-25, 28]

Results and discussion

In this study, an online survey had been spread amongst the construction professionals all involved in higher degree education sector with outstanding professional and practical background in the industry across the globe. Countries received the survey are Australia, Iran, Canada, India, US, and China. 49 survey delivered and 24 returned with response. The first question was designed to filter the socialist and capitalist school of thoughts. From that, 9 were classified as socialist and 15 were classified as capitalist indicating that the majority of the selected sample value the financial gain more than social benefits. Analytic Hierarchy Process had been run on the data received based on the objective, criteria, and models outlined in figure 3.

Which one do you usually set as an objective in projects?

○ Social welfare

○ Financial profit

As a measure to the productivity of a project, "Innovation" is more important than "Automation" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

As a measure to the productivity of a project, "Innovation" is more important than "Environmental impacts" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

As a measure to the productivity of a project, "Innovation" is more important than "Shareholders' satisfaction" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

As a measure to the productivity of a project, "Automation" is more important than "Environmental impacts" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

As a measure to the productivity of a project, "Automation" is more important than "Shareholders' satisfaction" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

As a measure to the productivity of a project, "Environmental impacts" is more important than "Shareholders' satisfaction" by a factor of:

○ 1/5 ○ 1/3 ○ 1 ○ 3 ○ 5

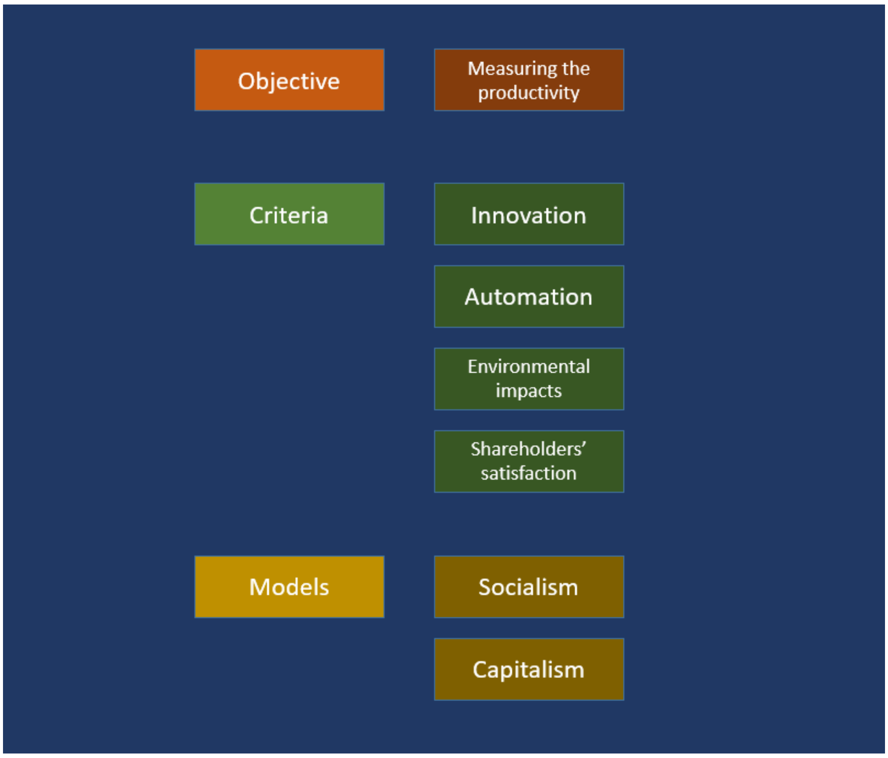

Figure 4 Structure of AHP model to identify the level of productivity in Capitalism vs. Socialism

The average of the scores received from the surveys were calculated. Two comparison matrices indicating the socialist point of view on one flip and the capitalist point of view on the other were formed as followed:

$$Soclaisit\ results = \begin{bmatrix} 1 & 1.132 & 0.613 & 1.666 \\ 0.883 & 1 & 1.058 & 1.799 \\ 1.630 & 0.945 & 1 & 1.873 \\ 0.600 & 0.556 & 0.534 & 1 \end{bmatrix}$$

4.114 3.633 3.205 6.338

$$Capitalist\ results = \begin{bmatrix} 1 & 2.085 & 0.923 & 1.408 \\ 0.480 & 1 & 0.818 & 1.094 \\ 1.084 & 1.223 & 1 & 2.456 \\ 0.710 & 0.914 & 0.407 & 1 \end{bmatrix}$$

3.274 5.222 3.148 5.958

Normalized comparison matrices were resulted from the division of each array by the sum of each column.

$$Normalized\ soclaisit\ results = \begin{bmatrix} 0.243 & 0.312 & 0.191 & 0.263 \\ 0.215 & 0.275 & 0.330 & 0.284 \\ 0.396 & 0.260 & 0.312 & 0.296 \\ 0.146 & 0.153 & 0.167 & 0.158 \end{bmatrix}$$

$$Normalized\ capitalist\ results = \begin{bmatrix} 0.305 & 0.399 & 0.293 & 0.236 \\ 0.147 & 0.191 & 0.260 & 0.184 \\ 0.331 & 0.234 & 0.318 & 0.412 \\ 0.217 & 0.175 & 0.129 & 0.168 \end{bmatrix}$$

The weighted score of 4 predefined criteria known as innovation, automation, environmental impacts and shareholders' satisfaction based on the socialist or capitalist point of view are listed below:

Table 5 Weighted results AHP model on surveys received

	Socialist	Capitalist
Innovation	25.2%	30.9%
Automation	27.6%	19.5%
Environmental impacts	31.6%	32.4%
Shareholders’ satisfaction	15.6%	17.2%

The results of AHP analysis shown in table 4 proves that the rate of innovation in capitalism is considerably higher than countries ruled by socialism way of thinking. This is also match the findings from the WIPO charts in regards to the number of patent grants showed in figure 1. Among all, the environmental impact of construction projects was nominated as the highest ranked criteria to evaluate the productivity of the projects. Another significant finding was the higher score of automation in socialism compared to capitalism. This can be due to the fact that since construction participants lack in motivation to accomplish tasks more efficiently (mainly because of the overly cautious risk aversion), the tendency to automation is much higher. In other words, the participants wish the tasks being accomplished automatically with less effort.

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Through the process of questionnaire data collection, the participants had consented the use of information provided anonymously. The online data collection system did not require personal information of the participants and the submission of the questionnaire would be granted only after the consent was given. Hereby, the authors gratefully appreciate the participation of opinion leaders in helping the progress of this research. Also, the authors appreciate the financial support received by both the Institute of Construction Materials and Western Sydney University upon the progress of this article.

Conclusion

Based on the data obtained and analysed, for middle-eastern countries in order to yield a higher productivity rate, governments must provide incentives for private sectors to compete in such a way that innovation being appreciated more. This is due to the roughly 5.7% lower weighted results of AHP model for measuring the innovation incentives based on the data collected. On the other side of the flip where the productivity in capitalist perspective is being assessed, authorities must provide more incentives and motivation for industry and academia by investing in R&D projects those are aiming to develop automated machines for construction purposes. This is due to 8.1% lower weighted results of AHP model for automation incentives based on the data collected. Both environmental considerations and shareholder's satisfaction are highly appreciated in both school of thoughts.

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Advanced technological implementation of construction and demolition waste recycling

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Abstract

In the shade of rural development plans and the constitution of sustainable environmental construction practices, the utilization of construction and demolition waste recycling becomes significant more than ever in order to protect the human built environment from the consecutive impacts. During the past couple of decades, the implementation of recycling techniques had been improved in such a way that, for example, Australia is domestically producing a considerable amount of recycled aggregate and uses such material in the applicable construction areas such as road pavements and concrete products. This paper is inspiring the use of Internet of Things and a novel approach for the consumption of recycled aggregate in concrete, called CO_2 Concrete. Data had been collected from the interviews with the industry senior experts. Extensive literature review and the data resulted from laboratory experiments on the use of recycled aggregate in concrete contributes to the body of the present paper. Also, a set of computer programs had facilitated the deployment of Internet of Things in practice.

Keywords:

Sustainable development; Construction automation; Recycled aggregate

Introduction

In the shade of the global population growth and the increasing demand for housing and civil infrastructure, the need for sustainable urban development becomes significant[1-3]. Construction sector is known as one the most environmentally impactful human activities across the varieties of industries by having a high rate for extraction of raw materials and natural resources. The tendency of environmentally conscience communities and enterprises is not only to recycle a large percentage of construction and demolition waste, but to aim for zero waste, which means ensuring that all products be made to be reused, repaired or recycled back into the marketplace. Zero waste plans have been adopted in developed economies around the world and by the local governments in Australia and New Zealand. Due to this rapid growth of population and the deriving need for a wider infrastructure, the construction industry is booming in the middle-east with 117 mega projects totaling in 1 trillion Tomans worth of value[4]. This indicates the necessity of implementing a comprehensive construction and demolition waste recycling plan in the region before environmental impact of waste generated becomes a dilemma. Recycled aggregate is produced at mobile or fixed centralized crushing operations, where the construction and demolition waste are being delivered. The crushed materials are being screened to produce products of desired size distribution. Recycled aggregate had shown to be an effective alternative to natural aggregate to meet the increasing demand for road construction materials as road base or subbase since it provides sufficient mechanical properties including bearing capacity, resilient modulus and specific gravity [5-7].

Nikmehr et al [8] states that the main reason for construction and demolition waste generation in middle east is due to the lack of skills and experience of construction workers. She had also stated that the lack of awareness for the importance of recycling is another major contributing factor in the middle east. The ranking of main causes of waste generation on construction sites had been reported as followed in the same study:

1. Lack of knowledge of construction workers
2. Prevalence of traditional methods of construction in middle east
3. Lack of knowledge of demolition contractors
4. Wasteful use of materials on-site
5. Inappropriate packaging
6. Low quality of building materials
7. Inappropriate methods for handling on-site
8. Inefficient procurement
9. Inappropriate inventory
10. Inappropriate methods for shipment
11. Frequent demolition

Addressing the first, sixth, eighth, and ninth items this paper proposes the implementation of robotics in construction for the 1st issue, utilization of CO2 Concrete technology for the 6th item, and an organizational structure for the other 8th and 9th issues.

Kartam et al. [9] states that prior to establishing e recycling mechanism there are requirements to be met. In a free-market situation, he suggests that price and quality dictates the acceptance of system or a product. A shortage of both natural aggregate and access to landfills is known as to be an effective method encouraging the use of recycled aggregate. An organized collection and transportation of recycled aggregate ensures the reliable supply of suitable recycled materials. In terms of the mechanism behind the correlation of price, quality, and quantity of recycled aggregate, "*The general theory of employment, interest, and money*" [10] is a proven theory almost for a century now. The shortage of natural aggregate and limited access to the landfill sites can be achieved by government intervention via the means of taxation instruments. The organization structure proposed in this paper, also, provides a systematic approach towards the implementation of construction and demolition waste recycling.

Methodology

Field observations and interviews in Hamedan, Iran, allow the planning to be classified in the best appropriate manner by taking the industry's demand into account. These include interviews with concrete batching plant operators to identify the existing demand for the consumption of recycled aggregate. Also, the observations from the landfill sites reveal the quantity of supply of construction and demolition waste as the input capacity for the recycling plants.

In order to address the issues encountered with the participation of skilled and educated construction workers, this paper proposes the utilization of automation that decreases the impact of human intervention in construction activities, not to mention the promotion of productivity in the sector. Narrowing down in this aspect, principles of electronics had been taken into practice to develop a wireless device which is able to be scaled in an autonomous IoT (Internet of Things) system.

To ensure the high quality of recycled aggregate being delivered to consumers, laboratory tests had been conducted evaluating the performance of CO_2 Concrete that resulted a promising approach to enhance the variety of mechanical performance of concrete including compressive strength, workability, permeability, durability and shrinkage.

At the end, based on the principles of human resources and construction managements, an organizational chart had been proposed which ensures the effective 10 long-term strategic plans.

Discussion

Before any planning for the utilization of construction and demolition waste recycling in any part of the world there's a need for the evaluation of the systematic infrastructure exist. This includes but not limited to having (a)a proper overlook on the number of trucks available for the deposition of the wastes; (b) an understanding on the specification of crushers type available; (c) an overview on the neighboring of the region; (d) an understanding of the volume of waste generation and the concrete demand of the region. For the case of Hamedan, 20 trucks are available in the region particularly for this reason each with a loading capacity of 9-12 tonnes. Crusher is priced at 1.5 Billion Tomans. The construction and demolition wastes are being stacked up in Robat-e Sheverin close to the airport. The area in which the deposition of landfill occurs add up to a total of 390,000 m^2. Reports from site visits indicate that the average height of the landfill hill top reaches 50m in altitude. From that, the volume of current construction and demolition waste exists in Hamedan equals 7,500,000 m^3. Figure 1 below shows the condition and geolocation of the landfill area.

Figure 1 Actual footage of region subject to recycling plans. Above: The texture of the buildings in terms of materials used in the regional areas of Hamedan. **Below:** The volume of the landfills in Robate-Sheverin

In order to be able to consume the recycled aggregate produced in the plant, a quantified measure of the concrete demand in the region was required. The interviews with concrete batching plant operators shows that in the first half of the year when the weather is perfectly suitable for concreting, the total concrete production of all 15 concrete batching plants in the region are supplying 800 m^3 – 1000 m^3 per day. In the second half of the year, during the raining seasons, however, the concrete production capacity falls down to 450 m^3 – 650 m^3 per day.

Figure 2 Aerial view of the region subject to recycling services including the essential dimensions. Above: 20 km radius of service center to the deposition site. **Below:** Area of the landfill stack.

Robotics in construction

The modern construction practice requires the implementation of robotics more than ever due to increasing number of controls on health and safety, insurance costs, and labor wages. Although construction industry suffers from its high labor intensity, the emergence of self-driving cars equipped with artificial intelligence can be a promising approach towards a safer and more productive practices. Perhaps, Building Information Management (BIM) systems had been up-scaled significantly in the context of software development, still, the integration of BIM with construction machineries remains almost unattended. Smith states that [11] it is anticipated that up to 2.7 million US construction workers compromising almost half of the total workforce in the same sector would be replaced by robots by 2057. If true, sever social consequences arrive such as high unemployment rate, economic depression, increase in homelessness, etc. In fact, the driven factor for such consequences of automation returns to the idea that the business owners welcome labor cost savings for the promise of higher productivity [11-14]. Addressing the issues brought up by Smith, it can be seen as a rationale that robots are essentially being created to ease the human wellbeing. It is debatable that a number of jobs would be diminished caused by the presence of robots in the workplace, however, historically this trend had been in place since the beginning of humanity by the emergence of technological advancements.

From the technical point of view in the implementation of construction and demolition waste recycling facility in Middle-east, the utilization of IoT is planned which facilitates a wireless communication between machineries operating on site. The basic machineries required for recycling plants are crushers, screens, loaders, and trucks. A well-equipped plant powered by IoT needs an operation room where the machines could be controlled from there. Due to the complex mechanical structure of loaders and trucks, this research focuses only on the communication of operation room, crushers, and screens.

An electronic module had been assembled which makes the wireless communications possible. Arduino UNO (Figure 1 is the microprocessor which had been reinforced with the computer program below integrated with Blynk IoT cloud service:

```
#define BLYNK_PRINT DebugSerial
#include <SoftwareSerial.h>
SoftwareSerial DebugSerial(2, 3);
#include <BlynkSimpleStream.h>
char auth[] = "Null";

void setup()
{
  DebugSerial.begin(9600);
  Serial.begin(9600);
  Blynk.begin(Serial, auth);
}

void loop()
{
  Blynk.run();
}
```

The above program is a wireless switch to turn on/off a machine from a screen. The program will be installed down to the Arduino hardware which will be sending digital signals to the machine. The program is also simultaneously installed on the Blynk cloud service that communicates with the control system. In order to be able to run the recycling plant on IoT configuration pictured in figure 1, an Arduino kit will be hooked up with the power switch on the crusher. Once the switch button in the operation room had been turned on, the Blynk signals the Arduino kit on the crusher which turns the machine on for operation. This approach ensures the safety of construction workers and can be seen as a reduction in insurance costs. The vibrating sieves could be also operating in the same manner by the utilization of IoT.

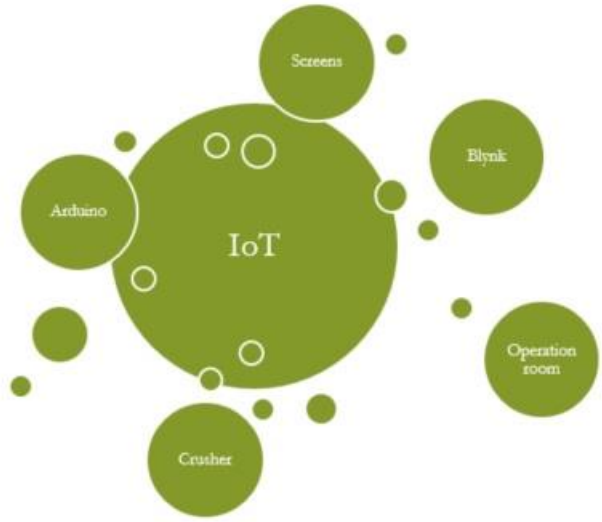

Figure 3 Schematic view of IoT integration

The present electronic module operates in low voltages of about 5V. However, to power up high voltage machineries, a 3 Phase power is suggested to be utilized.

The current cloud based system is functional on Android and iOS devices. Further explorations on the application of an operation software for Windows devices reveals the suitability of using C# codes to develop a well-tailored software. The C# codes could be modified based on the order specification of the project regulator/owner depending on types of the machineries being procured for project delivery. However, for the sake of this research, the following codes had been compiled successfully with the results shown in figure 4. In a nutshell, the program reads the data received from the software windows and based on the conditions in place commands the hardware to operate. In this example a ON/OFF switch would be signaled, although it can be running more complex functions such a controlling a conveyor belt with variable speed.

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;

namespace Arduino_Switch
{
    public partial class Form1 : Form
    {
        public Form1()
        {
            InitializeComponent();
            serialPort1.Open();
        }

        private void radioButton1_CheckedChanged(object sender, EventArgs e)
        {
            serialPort1.Write("A");
        }

        private void radioButton2_CheckedChanged(object sender, EventArgs e)
        {
            serialPort1.Write("J");
        }

        private void radioButton3_CheckedChanged(object sender, EventArgs e)
        {
            serialPort1.Write("B");
        }

        private void radioButton4_CheckedChanged(object sender, EventArgs e)
        {
            serialPort1.Write("J");
        }
    }
}
```

Figure 4 Windows software demonstration of the system used in operation room to control the machineries.

CO_2 Concrete

Previous case studies on the supply chain barriers in the use of recycled aggregate [15] reveals that due to the high water absorption of recycled aggregate, concrete batching plants are not eager to use such environmental material in their mix. The new emerging technology called CO_2 Concrete is aimed to enhance the properties of recycled aggregate. The process involves the injection of carbon dioxide in a physical interaction of the gas with recycled aggregate placed in a pressure chamber for a certain duration of time [16]. The porous structure of recycled aggregate, initially, compromises a few performance issues with the concrete made all of the binded to the high water absorption. These issues namely are *faster slump drop*, *higher shrinkage, lower workability, higher permeability, higher corrosion rate, lower compressive strength*. Such issues, in fact, are the reason to the lack of interest amongst concreters to use recycled aggregate in their products. The driving initiative behind the proposal of CO_2 Concrete technology returns, first, to the respectful implementation of sustainability principles, and secondly, the financial benefits gained as a result of lower costs for the supply of concrete ingredients. An initial investigation on the market capacity had indicated the 1/6 as the ratio for the unit price of recycled aggregate over the unit price of natural aggregate. The CO_2 Concrete is advantageous since it resolves the performance issues encountered with the use of recycled aggregate in concrete. The physical interlock of CO_2 gas inside the pores increases the density of aggregate and thus reduces the water absorption causing the relevant issues disappear. Butera et al. [16] extensive studies on the mechanical performance of CO_2 concrete made with recycled aggregate is partially summarized in the following table 1. The first column indicates the replacement ratio of natural aggregate with recycled aggregate.

Percent replacement (%)	Chamber duration (min)	Chamber pressure (KPa)	Slump drop (mm)	28 days Compressive Strength (MPa)
0	0	0	160	32.14
30	0	0	150	33.46
100	0	0	140	25.7
30	30	75	130	34.28
100	30	75	220	21.66
30	30	150	140	31.51
100	30	150	210	19.46
30	90	75	140	35.19
100	90	75	190	22.22
30	90	150	150	32.36
100	90	150	210	27.37

Table 1 Mechanical performance of CO_2 concrete made with recycled aggregate

Organizational structure

Addressing the issues stated by Nikmehr et al. [8] in regard to lack of effective procurement method and inventory/asset management, the present project in Hamedan follows the organizational structure as pictured in Figure 2. The IT department is committed to ensure the secured and consistent communication of machineries. Using GPS systems, the movement of trucks could be tracked that the data collected and stored on the cloud could be used by accounting and finance department. Sales department will be promoting the recycled aggregate product targeting concrete batching plants and road pavement contractors. Operations is responsible for the management of trucks and crushers. The Office or Real Estate, on the other side, is ought to arrange the commissioning of land, utilities with respect to the use of renewable energy. Security must be present at the plant gateway to ensure the secure access to the facilities inside the plant. Also, as the project is set to have the participation of international experts a comprehensive secure banking system is required allowing the transactions between different regions.

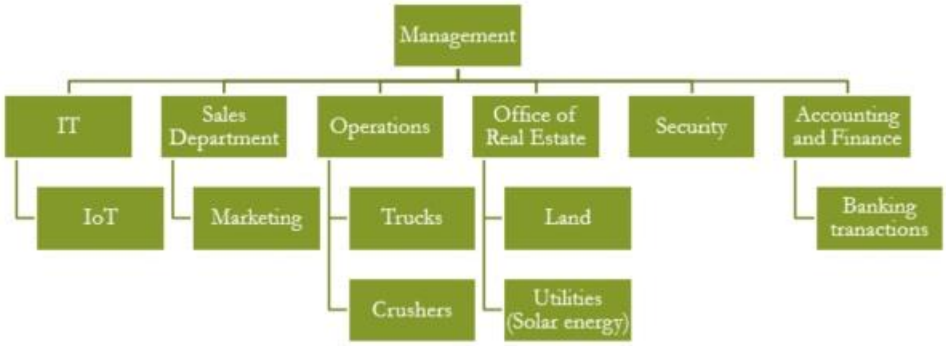

Figure 5 Organizational structure of the construction and demolition waste recycling plant in Hamedan

Regarding the financial viability of the entity, it has been stated during the interviews that since the cost of mining explosions are rising in the middle-east, the use of recycled aggregate is a perfect environmental alternative in that regards. Critically thinking, if the consumption of recycled aggregate reaches to the point where it passes the use of natural aggregate, the demand for demolition would increases ultimately which is not a sustainable approach as the service of life the buildings decrease.

Acknowledgement

This research could not be accomplished without the facilitation of the Institute of Construction Materials' technical staff members, supervisors and fellow academics. The Institute of Construction Materials (ICONSMAT) had also provided an unforgettable support both in the progress of this research financially and by providing data from field observations. The Hamedan's state authority had provided valuable resources towards the path for accomplishments of this project. Special thank goes to the Housing Foundation of Iran for regulating and providing the necessaries required for the accomplishments of this paper.

Conclusion

A set of issues exist in the implementation of construction and demolition waste recycling including but not limited to: lack of skilled workers in the sector; inefficient procurement method; and inefficient inventory. This case study presented the considerations and the methods employed in Hamedan, Iran upon implementing recycling plant operations in order to address the main three issues. Utilization of robotics, CO_2 Concrete technology, and an appropriate organizational structure are discussed and agreed to be effective methods. Utilization of robotics in the designated recycling plant is based on the IoT analogy where the electronic devices are able to communicate via wireless connection. CO_2 Concrete technology had been promoted which prior to the implementation in the full commercial scale requires a bigger carbonation chamber. The performance of CO_2 Concrete in the laboratory scale, however, shows a promising results. At the end, the organizational chart presented is planned to be implemented in Hamedan's recycling plant. The financial budgeting of the departments proposed are still in negotiation.

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A review on graphene reinforced cement composite: technical approach for ecofriendly construction

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Abstract

Graphene as an emerging material compromising outstanding properties had shown a great potential for commercial application in many industries including construction. The current paper seeks to review the advancements in the area of building and construction by focusing on the composition of graphene reinforced cement paste. The potential areas enhancing the performance of conventional cement mortar by graphene had been identified and investigated with a practical perspective based on the existing advancements. Mechanical properties, electrical conductivity and storage capacity of graphene for the purpose of producing an exposed concrete sample with the energy generation capacity had been briefly also studied. The results show that if a proper commercial synthesis method emerges for reducing the unit price of graphene, a graphene reinforced cement paste is a suitable material for ecofriendly high performance construction purposes. Following this result, the Australian market capital undergone a financial research where the graphene was subject as the commodity. A comparison had also been made between the environmental impact of graphene and cement.

Keywords

Graphene; Cement; Sustainability

Introduction

Graphene has recently attracted significant attention from the scientific community because of its extraordinary mechanical and electrical properties. In this paper, properties of graphene are being first explained followed by the barriers encountered with the commercial usage of graphene in construction practices. The state of ecofriendly construction approach utilizing graphene had also been mentioned in the following by promoting the production method of carbon nano particles from CO2 gas. Another fact that wears the graphene reinforced concrete an environmental dress is the results from the compressive tests which shows that the use of cement can be limited by a drastic rate, keeping the compressive responses constant.

Recent mechanical experiments have shown that graphene is the strongest material measured so far. This opens up opportunities for graphene as a nanomechanical material to be used in variety of industries including construction. The mechanical properties of graphene under tension have been investigated extensively using both experiments and atomistic simulation methods [1]. Carbon nanotubes and nanofibers were explored as promising promoters for reinforcements in cement-based materials at nanoscale [2, 3]. Graphene is consist of a one-atom-thick planer sheet comprising a sp^2 –bonded carbon structure with exceptionally high crystal and electronic quality [4-7]. Graphene intrinsically has a high thermal conductivity of 3000 W/mK [8] which can be seen as a solution for the high heat generation upon the development of the hydration reaction. The unique mechanical properties of graphene attract attentions for the potential applications in construction. Theoretical and experimental results on individual graphene nanosheets exhibit extremely high values of Young's modulus of about 1000 GPa and fracture strength of about 125 GPa[9].

Agglomeration of graphene particles caused by the process involved in the mass synthesis and the van der Waals forces between the nano platelets brings issues for a wider mechanical application. It compromises a hydrophobic characteristic which brings difficulties for its concrete application in terms of homogenous dispersibility by considering its low solubility in water[10]. On the other hand, the same hydrophobic characteristic of graphene may result in a more workable concrete as it would have almost the same functionality as superplasticizers by accelerating the development of the hydration reaction. This roots from a more exposure of cement particles to water. However, the graphene oxide (GO) had shown a good dispersibility in aqueous solvents. It has also to be mentioned that GO nano sheets are performing electrical insulation. GO sheets bear various oxygen-containing groups, mainly epoxides and hydroxyls on their basal planes and carboxyls on the edges, which facilitates the dispersion of GO in water[3, 11]. Dan Li et. Al [12] show that the surface charge (zeta-potential) of GO sheets are highly negative when dispersed in water. Since most of the extraordinary characteristics of graphene is associated with the individual sheets, the homogeneous dispersion of graphene nanoparticles becomes significant[12]. Surface modification using effective dispersion and exfoliation methods are some of the solutions for these types of barriers. Another method to prevent agglomeration is to attach other molecules or polymers onto the sheets which also increases the impurity of the product to be seen as an adverse effect. As reported by Tang et al [13], due to the lack of appropriate industrial dispersion method, graphene once it's used in a composite forms an instable cluster which significantly lowers the efficiency as reinforcement. Kuilla et al[14], suggests the advancement of graphene dispersion in polymer composites in another literature. A well-structured graphene reinforced composite must perform a modified interfacial area by producing a co-continues network[15].

Despite the fact that many studies in the field of nanoscience show the high dispersibility of GO sheets in aqueous solutions, S. Ghazizadeh et al. [16] argues that GO nanosheets aggregate in the Portland cement paste as it reacts with divalent and trivalent cations as well as hydroxide ions present in the paste solution causing the loss of oxygen groups. The reduction of GO in alkaline solutions had also been reported in other studies (apart from the construction related articles). This switches the repulsion between GO sheets to attraction and thus, the agglomeration of particles. In another research done by A. Hassani et al. [17], it's been claimed that based on the FE-SEM test results there were no aggregation of GO flakes had been found indicating a proper dispersion of nano particles in the cement paste. The controversy, thus, still remains for further investigations.

Many research studies reported an average enhancement in the compressive strength of graphene reinforced cement paste. The major effect of nanoparticles on the cement paste is the acceleration of the hydration reaction whereas 1D and 2D nanosheets are not only accelerate hydration but also reinforce the cement matrix due to their high aspect ratio[18-20]. It's been reported that the introduction of 0.05%wt GO can increase the compressive strength of cement paste by 15-50% and the associated flexural strength by 41-60%. The stress-strain curve derived from the experimental test on GO reinforced cement paste illustrate a longer portion of the plastic zone indicating the higher flexibility and a lower brittleness compared to the samples with no GO content [21, 22]. The main reason suggested and agreed across the scholars roots from the nucleation of calcium silicate hydrates as XRD diffraction data shows growth of C-S-H gel in GO cement mortar.

Commercial production of graphene

Graphite, consisting of stack of flat graphene sheets, inexpensive and available in abundance from both natural and synthetic sources, is the main resource for the mass production of graphene[12, 23-27]. The suitability of the application of graphene in various industries arises the necessity of a commercially scaled production method. Currently there are three major methods for a mass production of graphene compared in table 1.

Table 6 Graphene synthesis methods

Method	Cost of production	Quality of the product
Electrochemical exfoliation	Low – fast production	Low – damage to the honeycomb lattice caused by the oxidation step
Chemical vapour deposition	High – high temperature and expensive substrate	High – Large area graphene platelets gain

Electrochemical exfoliation

This method involves the oxidation of graphite sheets in an electrolyte followed by ultrasonic dispersion. Studies show that the amongst the range of electrolytes including HBr, HCl, HNO3, and H2 SO4 only the electrolyte containing H2SO4 exhibit ideal exfoliation efficiency. Once H2SO4 solution (4.8 g of 98% H2SO4 diluted in 100ml of deionized water) was used as an electrolyte, the static voltage of +1 V was first applied to the graphite for 5-10 min, followed by a ramped up +10 V voltage for 1 minute. The low voltage application at the beginning helps the graphite becomes wet and prepared for a proper exfoliation. The electrochemical exfoliation of graphite sheets usually yields thick layers of graphene with small surface area. However, the modification of the acidity of the electrolyte and the voltage applied can enhance the quality of the final product[28-32].

Chemical vapour deposition

Among all the strategies to produce graphene, chemical vapour deposition (CVD2 secured the place as a high efficient method producing single-layer large-area graphene sheets. The process involves the introduction of gas species in the reactor while heat applies. This is where the hydrocarbon precursors decompose to carbon radicals on the metal substrate surface forming the graphene nanosheets. The metal substrate acts as a catalyst and also provides the base for the deposition mechanism. Ni and Cu are the two major widely used metal substrates in the graphene CVD process[33-35].

Decomposition of carbon dioxide into oxygen and carbon nano particles

The reduction of greenhouse gas emission had become one of the main concerns of governments and scientists for the past decades. Many absorption and decomposition methods had been suggested since in order to trap and store the CO2 gas for future consumptions[36-41]. A new area of study is emerging suggesting the conversion of carbon dioxide into carbon nano particles. For instance, one of the methods is to react the CO2 gas in a saline solution of CaCL2-NaCL-CaO to obtain carbonate ions and subsequently splitting the carbonate formation into graphene on a stainless steel cathode by conducting electrochemical decomposition[42]. Other studies show the possibility of producing high quality carbon nanotube from carbon monoxide[43-45]. Carbon monoxide itself can be synthesised easily by thermal decomposition of CO2 into CO and O2.

Application areas of graphene reinforced cement mortar

Photovoltaic concrete panel

To have a proper understanding of the electrical conductivity and storage capacity of graphene, it is better to first identify the general relevant terminologies in the area:

Current-voltage (I-V) characteristic: As the name suggests, the I-V characteristics curves show the relationship between the current flowing through an electronic device and the applied voltage across it terminals. The following figure shows the I-V characteristics of an ideal resistor.

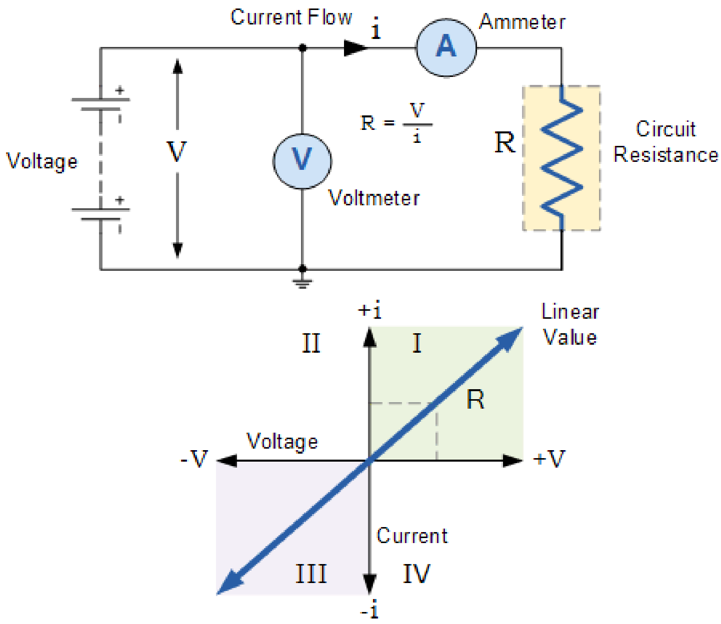

Figure 5 schematic current voltage characteristics of ideal resistors

Short circuit current: Is the associated current where the zero voltage applied.

Open-circuit voltage: Is where the I-V curve intersects with the horizontal axis representing voltage value at zero current.

Fill Factor: Is defined as the area under the I-V curve where the maximum power occurred. The power, essentially is derived from the equation P= I.V.

For a typical photovoltaic solar panel as terms defined above the I-V and P-V (Power-voltage) curves and be depicted in the following figure.

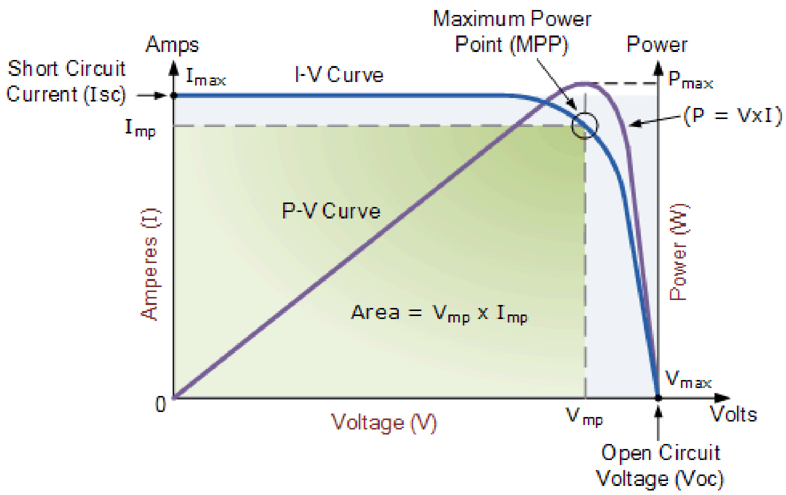

Figure 6 I-V and P-V graphs of photovoltaic cells

The excellent electron-transport properties and extremely high carrier mobility of graphene makes a suitable material for energy storage solutions and solar cells. Based on this, it has a great potential to be used for a low-cost, flexible, and highly efficient photovoltaic devices. The current–voltage (*I*–*V*) characteristics of the device showed a short-circuit photocurrent density (I_{sc}) of 1.01 mA cm^{-2} with an open-circuit voltage (V_{oc}) of 0.7 V, a calculated fill factor (FF) of 0.36, and an overall power-conversion efficiency of 0.26%. The relatively low I_{sc} and efficiency of this cell is related to the series resistance of the device, the relatively low transmittance of the electrode, and the electronic interfacial change. For instance, solar cells, based on a reduced graphene oxide film electrode with a sheet resistance of 40 kΩ sq^{-1} and a transparency of 64% had a conversion efficiency of 0.1%[46]; while a reduced graphene oxide film of 5 kΩ sq^{-1} and ≈80% transparency led to a device conversion efficiency of 0.4% [47]. Many efforts have thereby been made recently to improve both the conductivity and transparency of such graphene thin films to be used as electrodes in solar cells [48].

From the results of the experimental test on the electrical conductivity and the storage capacity of graphene nanosheets, the opportunity of developing concrete samples being capable of generating electricity arises. The current technology for solar energy generation compromises the use of silicon based material with NP-type poles. Studies show the enhancement of the efficiency of the solar panels made with graphene nanosheets[49-54]. It is reported that the photovoltaic graphene cells obtained the highest power-conversion efficiency recorded as 1.1%[51].The structure of a typical silicon base solar cell is demonstrated in the following figure:

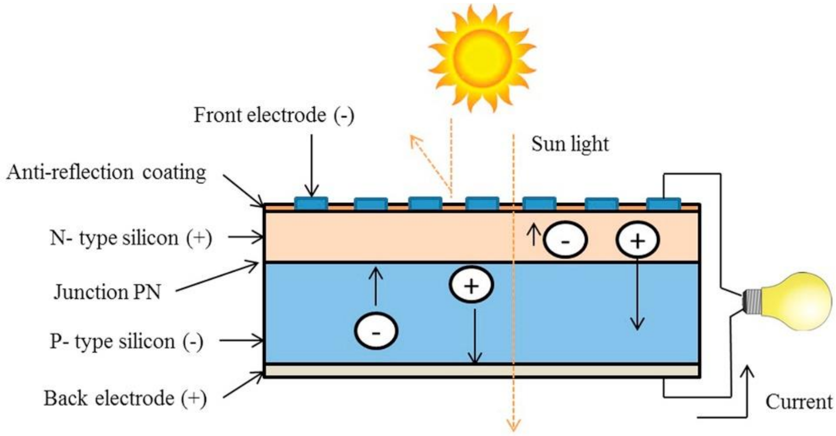

Figure 7 Schematic illustration of silicon based solar cells' functionality

A conceptual photovoltaic graphene reinforced concrete panel is anticipated to be capable of generating power, although in a much lower efficiency rate than a fully optimized solar cell, once it's been used in a high portion of concrete walls and slabs it can achieve a high energy yield.

Mechanical strength

Properly designed high quality graphene fibres can be seen as a tensile component of concrete panels to replace the conventional steel reinforcements. The fact that the graphene nano fibres represents a high tensile strength more than steel reinforcement and the light-weightness of such material brings the opportunity to develop lighter and stronger concrete panels. The reported 130 GPa tensile strength of graphene compared to the 1.5 GPa tensile strength of conventional steel reinforcement introduces the opportunity of reducing the cross sectional area of tensile reinforcement in the concrete composites by a factor of about 100[18]. This means that a 20 mm typical diameter of steel reinforcements can be replaced by a 0.2 mm thick graphene fibre exhibiting the same load carrying capacity.

Generally, the use of nanomaterials in cement composites results in a higher degree of hydration reaction. Carbon nano particles in particular had be investigated to represents an enhancement in the early age strength gain of cement composites[55, 56]. According to the literature review, an average 30% compressive strength improvement had been recorded once carbon nanotubes were added to the cement composites.

Table 3 Mechanical improvement of cement composite reinforced by carbon nano particles

Methodology	CNT weight fraction (%)	Results (% improvement)	Code

Ultrasonication	1	Compressive: SWCNT : 6% MWCNT: 30%	N.A.
Sonication and carboxylation with sulfuric and nitric acid	0.5	Compressive: 19% Flexural: 25%	N.A.
Sonication with Polyacrylic acid	0.045	Compressive: 50% Flexural: 10%	N.A.
Sonication with acetone and modified acrylic polymer and superplasticisers	0.5	Compressive: 11% Flexural: 34%	UNI-EN 196-1
Sonication and NaDC surfactant	0.2	Compressive: 29.50% Flexural: 35.45%	GB/T1 7671
Sonication and surfactant	0.08	Elastic Modulus: 35% Flexural: 40%	N.A.
Sonication and surfactant	0.08	Elastic Modulus: 45% Flexural: 25%	ASTM C348
Sonication and polyvinylpyrrolidone organic solvent	0.25	Load capacity: 47% Toughness: 25%	N.A.
Naphthalene-sulfonate plasticizer and modified polycarboxylate admixtures	0.3	Modulus: 14% Compressive: 12% Splitting tensile: 34%	NBR 7215, 8522 7222
Sonication, surfactant and swing centrifugation	0.08	Elastic Modulus: 35% Flexural: 35%	ASTM C348
Sonication and water reducing admixture ADVA cast 575	0.2	Flexural : 269% Ductility: 81%	N.A.
Sonication and polycarboxylate admixture	0.5	Compressive: 25%	N.A.
Sonication and surfactant (Brij35 and foam reducing agent)	0.05	Compressive: 40%	N.A.
Sonication and purified from carboxylated carbonaceous fragments	0.03	Compressive: 97.2%	N.A.
Sonication	0.5	Compressive: 15% Splitting tensile: 36%	ASTM C39 C496

Debulking, sonication and surfactant	0.048	Elastic Modulus: 75% Flexural: 50%	N.A.
Sonication and Gum Arabic surfactant with tributyl phosphate defoamer	0.08	Flexural toughness index: 57.5%	ASTM C1018-97

Thermal conductivity

The high thermal conductivity of the graphene provides the base for transferring the internal heat generated caused by the hydration reaction in concrete to the outer layers and thus, reducing the risk of the occurrence of early age cracking. The development process of hydration reaction in ordinary Portland cement is composed of several periods each having their own unique heat flow. These steps are commonly known as i. the initial period, ii. The induction period, iii. The acceleration period, and iv. The retardation period. This behaviour related mainly to three mechanisms, the silicate reaction, the dissolution of C3A and the precipitation of ettringite[57]. The early age cracking of concrete due to lack of sufficient curing treatment perhaps roots from the heat variation across the cross section of concrete element. The cracking becomes more significant in thicker concrete structure where the heat transformation zone becomes longer relatively. It might be of value to be mentioned that cracks generate due to the thermal gradient between layers. In terms of the time required for a proper curing, the use of Graphene in concrete will shorten this period as there would be less heat gradient in the cross section. A shorter curing period basically means less labour cost associated with the concrete projects as there would be less number of labours and hours required to take care of the poured concrete.

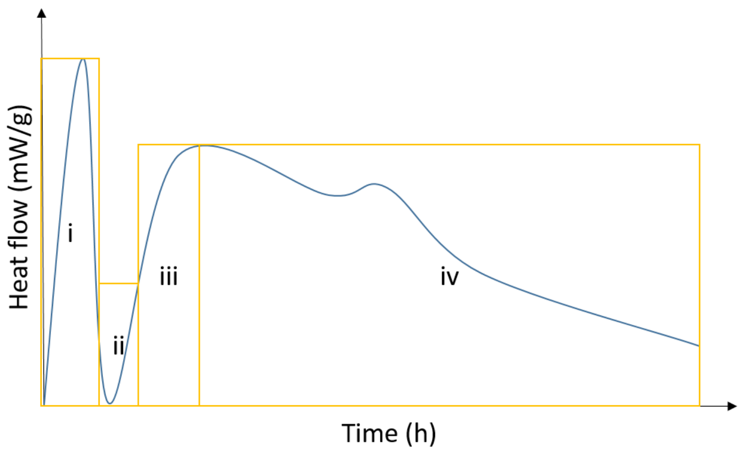

Figure 8 Hydration reaction enthalpy

The use of graphene in cement composite becomes beneficial once again in the context of thermal conductivity of concrete. A consistent heat transformation can be achieved reducing the chance of the development of the cracks.

Due to the fact that graphene presents a hydrophobic characteristic, and considering that the superplasticizers perform the workability solution based on the very hydrophobic characteristic, the use of graphene in cement composites is anticipated to exhibit a highly workable concrete with a right mixing method selected. Graphene, indeed, had been used in other industries as lubricant in order to reduce the friction.

Australian financial market position

As per May 2019, the data from the Australian Securities Exchange (ASX) reports a AUD$78.8 M market capital for graphene. This is at the same time as the 4 largest builder companies active in the construction industry report a total of AUD$19 B market capital. The Australian government is encouraging the industry leaning towards a more ecofriendly approach. Cement industry is one of the top ranked industries by carbon emission indices as production of each ton of Portland cement emits the same amount of carbon dioxide in to the atmosphere. The construction industry is leaning towards using Supplementary Cementitious Materials (SCM) in a wider scale in order to reduce the consumption of Portland cement in the benefit of environmental conservation[58]. Having an environmental perspective to the mass production of graphene, this material is more likely to be widely accepted in the Australian construction industry.

Environmental impacts of graphene production

Construction is identified as one of the most environmental hazardous industries across the globe. Enterprises, thus, are encouraged recently to adopt the sustainability and environmental construction approaches in their practices in many countries. Australia as a leader in the environmental conservation practices across the globe, puts restrictions and also motivators to employ the environmental approaches. Therefore, the succession of a project in Australia is closely dependant on the degree of environmental awareness. The financial aspects of graphene commercialization had been discussed in the previous section. However, it is less likely in Australia to achieve a higher market capital without a proper environmental evaluation on the manufacturing process of graphene nano particles.

Rickard Arvidsson et al. [59] reported the energy consumption of producing 1 kilogram of graphene from two separate routes known as ultra-sonication and chemical reduction of graphite as 470 MJ/kg and 1,100 MJ/kg respectively. This is while the green cement production reported to consume only about 3.3 MJ/kg ordinary Portland cement [60, 61].

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Conclusion

Based on the bibliometric analysis a gap had been identified between the studies conducted in the area of material science and the construction and building from 2008 until 2018. The present paper introduces the potentials of the use of graphene in the modern construction practices by focusing on sustainable construction principles. The photonic and electronic characteristics of graphene opens an area for development of a photovoltaic concrete panel to generate a portion of the electricity demand of buildings. Its outstanding mechanical properties had already showed satisfying results improving the compressive, tensile and flexural performance of cement composites made. The thermal conductivity and the hydrophobic characteristics are providing solutions for early age cracking and workability issues in concrete. However, the current high unit price of graphene is a barrier for a wider use of such material in concrete structures, thus, further detailed studies are required to facilitate the mass production by utilizing efficient processes for a wider use of graphene as a construction material.

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Electrical resistance of graphene reinforced cement paste

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Abstract

Graphene as an emerging material is compromising outstanding properties in a variety of sectors. In order to facilitate the use of graphene in construction practices, the current paper investigates the electrical resistivity of graphene reinforced cement paste with a perspective to utilized the enhancements. Graphene oxide had been synthesised using electrochemical exfoliation of graphite and replaced by ratios of 1, 3, and 5 to the mass of cement. Anodic and catholic exfoliation of graphite had shown contrasting results which will be discussed. Bulk electrical conductivity tests had been conducted at 7, 14, and 28 days. It had been observed that the addition of graphene oxide increases the electrical conductivity of samples. At the end, a brief financial review on the Australian market position reveals the possibility of accepting graphene oxide as a new type of supplementary cementitious material.

Keywords

Graphene; Cement; Electrical properties

Introduction

Graphene had attracted many attentions from almost all of the industrial sectors including construction due to its extraordinary mechanical and electrical properties. It a one-layer thick of carbon atoms bonded in sp^2 structure with an exceptional high crystal and electrical quality[1-4]. From the advantageous of using graphene in cement paste is the fact that since graphene has a recorded high thermal conductivity of 3000 W/mK [5] it can facilitate the curing procedure. The mechanism behind the facilitation of curing procedure can be rationalized in such a way that provides a path for the exothermic reaction of cement with water know as hydration. This way, the heat generated during hydration would escape the internal layers much faster in the presence of graphene in the mix. Internal cracking due to the temperature gradient is being avoided as the result.

Generally, the use of carbon nanoparticles in cement composites results in a higher degree of hydration reaction. Carbon nano particles in particular had been investigated as exhibiting an enhancement in the early age strength gain of cement composites. According to the literature review, an average 30% compressive strength improvement had been recorded once carbon nanotubes were added to the cement composites[6, 7].

In terms of solubility, studies report the agglomeration of graphene nanosheets in water due to hydrophobic characteristics[8]. The lack homogenous dispersion of graphene nano platelets would bring workability issues in concrete applications. Noteworthy that graphene oxide platelets, amazingly, compromise different properties in terms of dispersibility in contrast to graphene itself. The hydrophilic properties of GO sheets had shown lubricating effect once added in cement similar to the effect of superplasticizers [9, 10].

Graphite, consisting of stacks of flat graphene sheets and also ribbons of carbon attached is the main source for the mass production of graphene which is also in abundance both in natural and synthesised resources [11, 12]. Currently there are two major production method exist for graphene shown in table 1:

Table 7 Commercial production methods of graphene

Method	Cost of production	Quality of the product
Electrochemical exfoliation	Low – fast production	Low – damage to the honeycomb lattice caused by the oxidation step
Chemical vapour deposition	High – high temperature and expensive substrate	High – Large area graphene platelets gain

Electrochemical exfoliation involves oxidation of graphite sheets in an electrolyte followed by ultrasonic dispersion. Studies show that the amongst the range of electrolytes including HBr, HCl, HNO3, and H2SO4 the sulphuric acid had exhibited a highly efficient exfoliation. Once H2SO4 solution was used as an electrolyte, starting off with a low voltage for a few minutes from the beginning of electrolysis would allow the graphite to wet and prepared for proper exfoliation. The voltage applied could be ramped up after a while to speed up the process. The electrochemical exfoliation of graphite sheets usually yields thick layers of graphene with small surface area. However, the modification of the acidity of the electrolyte and the voltage applied can enhance the quality of the final product [13-16].

Chemical vapour deposition [10] amongst the methods proposed for the production of graphene is known as the most efficient technique which yields the highest ratio of single-layer large-area sheets. The process involves the introduction of gas species in the reactor while heat applies. This is where the hydrocarbon precursors decompose to carbon radicals on the metal substrate surface forming the graphene nanosheets. The metal substrate acts as a catalyst and also provides the base for the deposition mechanism. Ni and Cu are the two major widely used metal substrates in the graphene CVD process[17-19].

Seeking to develop a conductive concrete panel reinforced with graphene particles, this study evaluates the electrical properties of samples made with electrochemically exfoliated graphene. The test includes a measurement on the effect of voltage applied, density of graphite sticks, concentration of acid as electrolyte on the electrical conductivity of cement paste. The results would be beneficial in terms of introducing opportunities for conductive non-destructive health monitoring test on concrete.

Results and discussion

Cathodic graphite exfoliation

This technique refers to the process where graphite sticks are positively charged [20]. The 200 mL of 98% sulphuric acid had been solved in 10 L water in order to decrease the concentration to 2%. This was mostly due to safety considerations. The density of the graphite used for electrochemical exfoliation was recorded as 3250 kg/m^3. In the first attempt where 6 V DC current had been connected to the aluminium electrodes no sign of exfoliation had been observed in 30 min. The situation was the same even by increasing the voltage to 12 V. The measures read from the voltmeter one side connected to graphite itself the other to the negative charged aluminium electrode had shown 2-3 V potential differences indicating voltage drop in the acidic electrolyte.

A bit of explanation for the reasons behind the observations can refer to the ion sizes. In the sulphuric acid electrolyte, upon decomposition of the molecules, $2H^+$ and $SO4^{2-}$ are being produced. Where the graphite is positively charged a larger ion ($SO4^-$) facilitates the intercalation. In simple words, for the dense graphite samples with less openings it is hard to reach between the layers. The cathodic exfoliation in this study were subject to test for 48 hours and only a thin traces of black graphene layers had been observed. It is anticipated that even with longer exfoliation period the quality of the final product would be multi-layer thick GO (graphene oxide) sheets as a low quality result.

Anodic graphite exfoliation

This method, in contrast with cathodic exfoliation, places the negatively charged electrodes on the graphite stick [20]. In another attempt a looser graphite sample in terms of density had been used with a density of recorded as 2540 kg/m^3 subject to anodic exfoliation starting at the input voltage of 12 V DC in a 2% sulphuric acid with configuration as shown in figure 1.

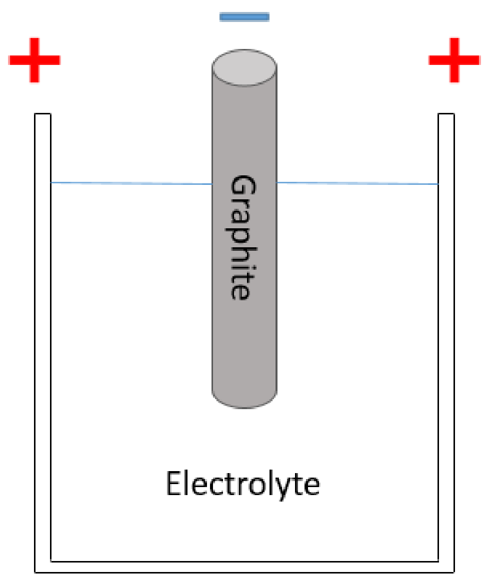

Figure 9 Electrochemical exfoliation apparatus assembled for this study

The graphite stick had exfoliated thoroughly after 24 hours. Using paper filters, the flakes of graphene oxide had been separated from the electrolyte. The filtration process had taken 3 days until dry particles obtained. Reasoning for the success of anodic exfoliation as opposed to cathodic method, Hydrogen ions are much smaller than sulphur ions in terms of size, and they are greater in numbers as each molecule of sulphuric acid decomposes into two hydrogens ($2H^+$) and one sulphur ($SO4^-$). In other word the intercalation of looser graphite sample is much easier with more (in numbers) smaller ions.

One of the mistakes undertaken during the experiments at the beginning stages was the submergence of aluminium holders in the acidic electrolyte. This delays the exfoliation process by considering the level of reactivity of the chemical elements. In such a reactivity series, aluminium stands on top of carbon in terms of yielding a higher reactivity in a corrosive environment.

Cement mix

Graphene oxide after exfoliation had been added to the cement paste with the mix design shown in table 2. The w/c ratio had been kept 0.3 constant in all of the samples to avoid the effect of such on electrical resistance. Graphene oxide had been added to the mix with the ratio of 1%,3%, and 5% to cement. Samples were placed on the vibrator for consolidation purposes for about 30 seconds. Overall, the preparation procedure is in compliance with Australian Standard code: methods of testing concrete [21]. Samples were demoulded after

24 hours of placement and cured in plastics wraps and soaked in water to keep the temperature constant at 22-25°C.

Table 8 Mix proportion of samples

	Cement	Water	GO
S0	600 g	200 g	0 g
S1-G1	600 g	200 g	6 g
S2-G2	600 g	200 g	18 g
S3-G3	600 g	200 g	30 g

Figure 10 From left to right: filter dried graphene oxide - mix portion - cured samples

Electrical resistance

Samples were tested for electrical resistance using the apparatus as shown in figure 2.

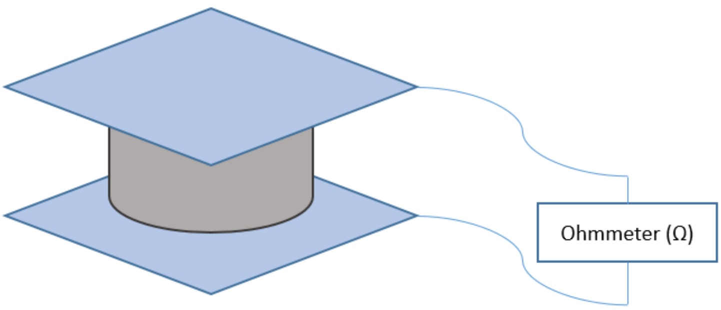

Figure 11 Apparatus used in the measurement of electrical resistance.

Concrete bulk resistivity is measured once two electrodes attached to the two ends of samples. The following equation results in a unified measure for concrete electrical resistivity:

$$\rho = R\frac{A}{l}$$

Where R is the readings from the ohmmeter in the unit of ohm. A is the cross sectional area and l is the length of the samples. Although this method is one of the widely acceptable approaches, it suffers from lack of accuracy due to the presence of metallic contacts which bridges the ohmmeter connection to the samples. The electrical resistivity test had been conducted in compliance with ASTM Standard C1202-10, AASHTO TP 95, and AASHTO Designation: T 358-151.

Each sample had undergone three readings. The electrical resistance of samples had been measured at the ages of 7, 14, and 28 days given the 10 cm average height of the cylindrical cement samples and the cross-sectional area of 19.625 cm^2.

Table 9 Results of electrical resistance test

	7 days	14 days	28 days
S0	152 Ω.m	210 Ω.m	246 Ω.m
S1-G1	124 Ω.m	142 Ω.m	183 Ω.m
S2-G2	92 Ω.m	122 Ω.m	156 Ω.m
S3-G3	61 Ω.m	88 Ω.m	110 Ω.m

The above table in conjunction with figure 3 are indications of the enhancements in electrical conductivity of concrete samples made with graphene particles. One of the important criteria which also needs to be addressed every time that the electrical conductivity of concrete samples is subject to discussion is the durability index. In our case, as the conductivity increases [11] the corrosiveness of the paste requires attention. Kessler et al. [22] suggest the following range in order to predict the corrosiveness:

- When $\rho \geq 120$ Ω.m: corrosion is unlikely
- When 120 Ω.m $\geq \rho \geq$ 80 Ω.m: corrosion is possible
- When 80 Ω.m $\geq \rho$: corrosion is fairly certain

Based on that, it is not recommended to reinforce samples containing graphene particles with steel rebars to avoid corrosion. Although lack of steel reinforcement might bring up concerns about the tensile strength of concrete specially for structural purposes, other studies [6, 7] had shown an average of 30% increase in flexural strength of GO reinforced samples which ease the concerns eventually.

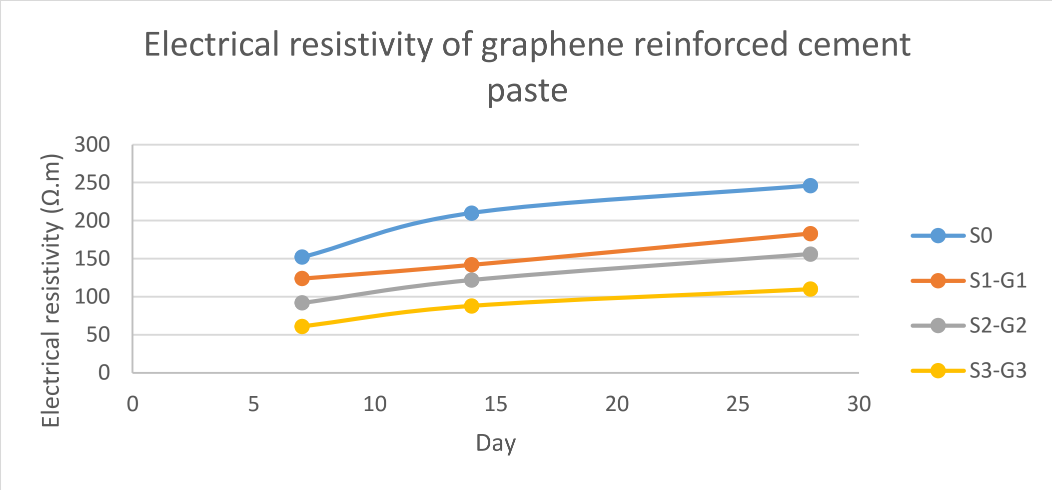

Figure 12 Electrical resistivity measures of samples reinforced with different portion of graphene oxide.

Australian financial market position

As per May 2019, the data from the Australian Securities Exchange (ASX) reports a AUD$78.8 M market capital for graphene. This is at the same time as the 4 largest builder companies active in the construction industry report a total of AUD$19 B market capital. The Australian government is encouraging the industry leaning towards a more ecofriendly approach. Cement industry is one of the top ranked industries by carbon emission indices as production of each ton of Portland cement emits the same amount of carbon dioxide in to the atmosphere. The construction industry is leaning towards using Supplementary Cementitious Materials (SCM) in a wider scale in order to reduce the consumption of Portland cement in the benefit of environmental conservation[23]. Having an environmental perspective to the mass production of graphene, this material is more likely to be widely accepted in the Australian construction industry.

Conclusion

The records from the laboratory experiments indicate in order to achieve a high yield exfoliation of graphite sticks into graphene particles, anodic exfoliation must be utilized as long as Aluminium electrodes are used. It is also important to be noted that since the Aluminium chemical reactivity stands on top of the carbon in the relevant series of reactivity, the negative electric carriers must not be submerged in the acidic electrolyte. The electrical resistivity of samples with higher graphene content had been enhanced. This can be seen as an opportunity to innovate concrete samples being able to produce electricity once NP-doped graphene particles were added in the mix.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Recycling of coal mining slurry in concrete mortar

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Abstract

Coal industry is the third largest mining activity in Australia by capital expenditure. Coal slurry is a mixture of solids and liquids produced by a coal preparation plant which is a by-product of run-of-min washed out. The coal slurry is traditionally being disposed in ponds which causes many environmental hazards. As part of associating with the Australian waste management plans, this paper seeks to evaluate the feasibility of coal slurry recycling by utilizing an appropriate technique in using such hazardous industrial waste in concrete production. As the solid particles of slurry tends to settle upon time, two different samples from different depth of the slurry each with specified solid contents have been obtained. The solid content of the slurry could be replaced partially with the cement content of the concrete mix. In other words, the coal slurry has studied to be an appropriate supplementary cementitious material (SCM). Compressive strength of 24 different cement mortar mix series has been tested in 7 days after pouring and water bath curing in the room temperature of 22-24°C.

Keywords:

Coal mining; Cement mortar; Waste treatment; Sustainable building materials

Introduction

In Australia, coal is mined in every state securing the third place in the ranking of the capital expenditure in all of the Australian mining industry. Coal mining occurs mainly in Queensland, New South Wales, and Victoria. About 75% of coal mined in Australia is exported, mostly to Eastern Asia. 202 Million Tons of thermal coal has been exported in year 2016 with a total value of $18,902 Million Australian Dollar[1]. Coal production in Australia increased 23.08% between 2012 and 2015 from a net 146,944 kt to 191,056 kt [2].

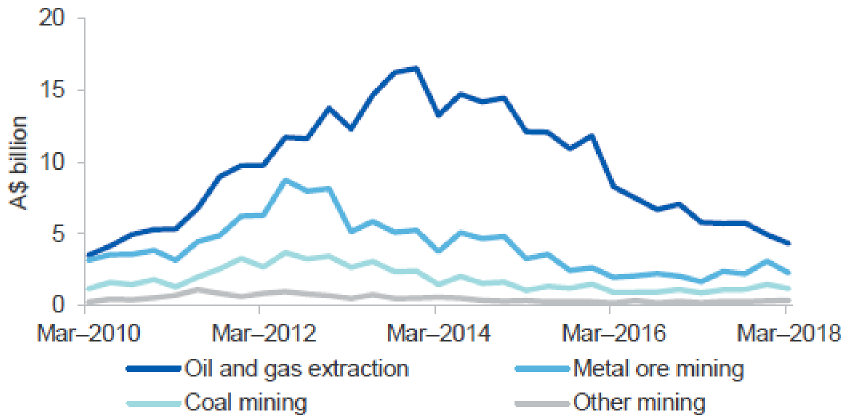

Figure 10 Australian mining capital expenditure

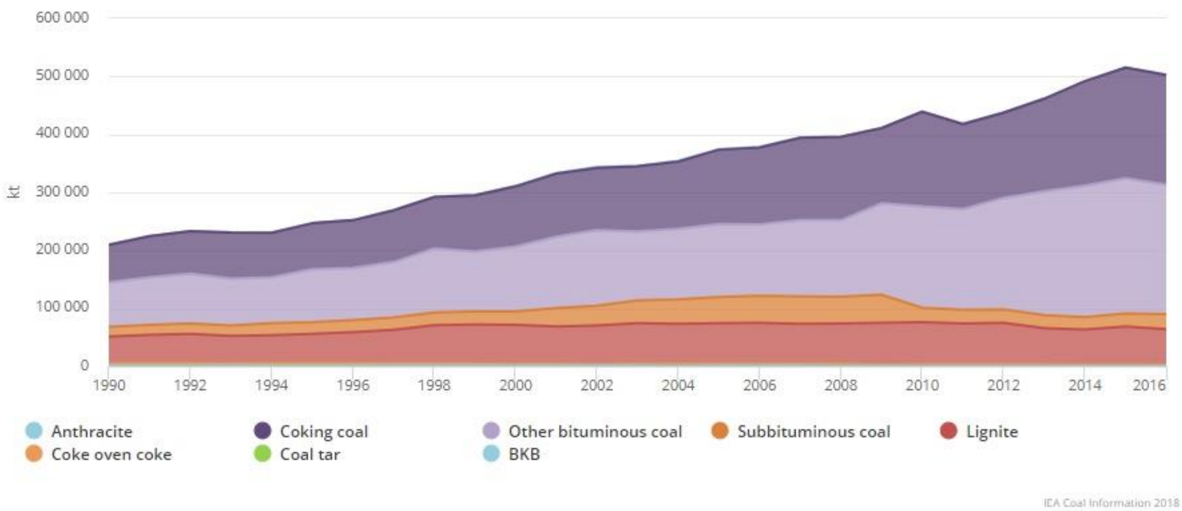

Figure 11 Coal production by type in Australia

Due to its high rate of greenhouse gas emissions, the coal industry has been criticized for many years for its effect on the global warming.

Cement industry, on the other hand, is one of the top ranked industries by the carbon emission indices as production of each ton of Portland cement emits the same amount of carbon dioxide in to the atmosphere. The construction industry is leaning towards using Supplementary Cementitious Materials (SCM) in a wider scale in order to reduce the consumption of Portland cement in the benefit of environmental conservation.

The recycling incentives in Australia is highly valued with a high 60% recycling rate of the total of 64 million tons of waste produced in 2014-2015. The quantity of material recycled in Australia increased significantly. - Recycling increased by 30% over the period from 27 to 35 Mt or 1.4% per capita per year. Waste policies and programs have been established at all levels of Australian governments— Commonwealth, state, territory and local. Policy and legislative responsibility for waste rests with the states and territories, and policy at this level has the greatest influence on waste management. Table 1 lists some of the main policy settings in New South Wales [3]:

Table 1 List of some the main waste policies in NSW

Landfill levy (2016-2017)	Strategy document	Targets to increase recovery rate	Other(Inc. landfill bans)
• Metropolitan area $135.70/t • Regional area $78.20/t • Virgin excavated natural material $122.13/t • Shredder floc metro $67.85/t • Coal washery rejects $14.20/t	NSW waste avoidance and resource recovery strategy 2014-21	By 2016–17, reduce litter items by 40% compared with 2011–12 then continue to reduce to 2021–22. Also by 2021–22: • reduce waste per capita • reduce illegal dumping in Sydney and the Illawarra, Hunter and Central Coast regions by 30% • establish baseline data to develop additional targets. By 2021–22, increase recycling rates for: • Municipal solid waste from 52% (in 2010–11) [4-6] to 70% • Commercial and industrial waste from 57% to 70% • Construction and demolition waste from 75% to 80%.	Hazardous waste tracking system in place. Container deposit scheme to be introduced in December 2017.

Aligned with the recycling initiatives, this paper seeks to propose a new recycling approach to reduce the environmental hazards caused by coal slurry by recycling such material in concrete manufacturing process.

Coal slurry

Coal is the Australia's primary source of energy for producing electricity. It is mined in two different methods including open-cut mining and underground mining. In open-cut mining, surface layers of soil and rock is removed in order to reach the mineral deposits. It is alleged that 65% of raw coal production in NSW is produced through the open-cut mining. In underground mining, many tunnels are created from the surface into the mineral seam to transport the equipment and machinery that extract the mineral material[7]. A by-product of the coal mining industry is a high viscose sludge which is conventionally being disposed in rivers to be washed out. After the mined coal is brought to the ground surface with its associated impurities, it is sent to coal preparation plant where the coal is separated from its impurities such as sulfur, ash, clay and rocks. The main purpose of coal preparation plant or coal washery is improving the quality of coal to make it suitable for market place[8]. The conducted process in coal preparation plant can be generally divided into four basic phases:

- Initial preparation,
- Fine coal processing,
- Coarse coal processing,
- Final preparation.

The majority of the coal cleaning processes including the use of upward currents or pulses of water fluid fluidize a bed of impurities and crushed coal. In this way, lighter coal particles rise and can be removed from the top of the bed. In the following, cleaned coal is dried in the final preparation processes.[9] Coal washing is primarily based on the differences in specific gravity between coal and its impurities since most of its impurities are heavier than it[10]. The coal washery generates a huge amount of liquid waste solid waste called coal slurry that they have been considered as a serious environmental threat in recent years. According to ABS Water Account, within the NSW mining industry, coal mining makes up 58% water use between 2008 to 2009[11]. Another source of generating coal slurry is the aspiration engineering unit in which pure water is used for the removal of dust particles and the purification of air to ensure the safety of workers[12]. The most conventional method for disposing coal slurries is using tailing storage facilities (TSFs), where they are high potential areas to cause serious environmental problems. Slurries are stored on the top surface of these facilities for either reclaiming the water when required for processing operation or water reuse. TSFs have very low surface bearing strengths which make them hazardous areas to human and wildlife over a long period of time. Tailing dams' failure has always been a serious environmental thread for the contamination of surface waters and aquifers that can be occurred due to seepage and erosion of the contaminant facilities, blockage, and insufficient capacity of spillway systems which leads to overtopping[13, 14]. Sustainable alternative proposals to tailing dam disposal include dewatering of coal tailing slurries usually by mechanical dewatering methods such as sedimentation followed by filtration. These new innovative methods provide various advantageous including water conversation, reduced percolation into the environment, contaminant prevention requirements, more efficient water management, and a dry disposal method. In this method, flocculants with specific characteristics such as molecular weight, charge density and dosage, etc. are added to coal slurry which lead to destabilizing the fine particle suspension and the formation and growth of aggregate subsequently[15].

Application of coal slurry in concrete production

The coal slurry used for the purpose of this study is obtained from underground coal mining in NSW. Two types of polymers have also been used in the mix.

The solid content of the coal slurry samples has been calculated based on oven drying methods in a temperature of 105 Celsius degrees and duration of 6 hours. For the first 3 samples (S1-S3) 13.36, the solid content has been recorded as 19%, for samples S4 and S5 a solid content of 68% has been calculated. Samples S6 to S13 have been mixed with oven dried coal slurry (100% solid content). In Samples S6 to S9 attempt made to evaluate the effect of replacement of sand by coal slurry. S9 shows lack of flowability/workability by formation of flocs. In samples S10 to S12 the effect of cement replacement of 20%,40%, and 60% by dried coal slurry have been challenged.

Three extra mix series have been prepared containing fly ash as a replacement by cement with ratio of 30%-50%-70%. These series of mix aimed to bring the advantage of being eco-friendly as no cement has been used in the mix. These set of samples took 4 days to reach the harden state, which indicates lack of development in hydration. This roots from the chemical composition of coal slurry which does not include sufficient amount of CaO required for hydration reaction.

Three other mix series have also been prepared to evaluate the effect of blast furnace slag as a replacement of cement with the ratio of 30-50 and 70%. But, similar to the previous samples mixed with fly ash, the hydration reaction showed almost no significant progress during the first 2 days. It has to be mentioned that based on the researcher’s observation, series of mix containing slag showed more hydration development compared to fly ash. The following table shows the mix design of these six mix series containing fly ash and slag.

Table 2 No-cement content samples with no responses of compressive strength and early stage hardening

Dried slurry (g)	Fly ash (g)	Slag (g)	Sand <5mm (g)	Water (g)
147	0	63	600	130.2
105	0	105	600	130.2
63	0	147	600	130.2
147	63	0	600	130.2
105	105	0	600	130.2
63	147	0	600	130.2

The reason behind the lack of progress in the hydration reaction lies on the chemical composition of cement, fly ash and slag. The hydration reaction at the first stage requires a considerable amount of calcium silicate and calcium aluminate minerals. The early stage strength development occurs due to the reaction of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) with water following the equations below [16]:

$$C_3S + (1.3 + x)H \Rightarrow C_{1.7}SH_x + 1.3CH$$

$$C_2S + (0.3 + x)H \Rightarrow C_{1.7}SH_x + 0.3CH$$

Data gathered and processed from 9 Australian fly ash quarries shows an average value of the chemical composition of the fly ash to be in table 3 [17]. The chemical composition of typical slag collected from china Steel in Kaoshiung [18] and standard Portland cement [19] is also provided in table 3 for comparison:

Table 3 Chemical composition of supplementary cementitious materials[20, 21]

	SiO_2	Al_2O_3	Fe_2O_3	CaO
Fly ash	59.04%	26.27%	7.4%	2.02%
Slag	34.39%	14.47%	0.63%	41.67%
Cement	22%	5%	3%	63%
Wollastonite	49.48%	0.70%	0.40%	45.36%
Silica fume	92.10%	2.04%	1.08%	0.45%

As the early stage strength has not been observed for the past 6 mix designs provided in table 2, it can be concluded that the reaction of tricalcium silicate and dicalcium silicate has not been developed in the exposure of the dried coal slurry sample.

Samples S13 to S15 were designed to evaluate the effect of polycarboxylic based superplasticizer in order to enhance the flowability of the mix while more percentage of sand is being replaced by dried coal slurry. Superplasticizer by an amount of 3% of the cement mass has been added to the mix and the water content of the mixture has been reduced by 25% to the water/cement ratio of 0.46.

Table 4 concrete mortar mix design

	Cement(gr)	Sand <5mm (gr)	Water (gr)	Slurry type 1 (gr)	Slurry type 2 (gr)	Dried slurry (gr)	Polymer type 1 (gr)	Polymer type 2 (gr)
S0	210	600	130.2	0	0	0	0	0
S1	210	600	58	116	0	0	0	0
S2	210	600	20	92.8	0	0	18.56	0
S3	210	600	30	108	0	0	0	12.6
S4	210	600	93	0	116	0	0	0
S5	210	600	90	0	200	0	0	0
S6	210	500	130.2	0	0	100	0	0
S7	210	400	130.2	0	0	200	0	0
S8	210	300	130.2	0	0	300	0	0
S9	210	200	130.2	0	0	400	0	0
S10	168	600	130.2	0	0	42	0	0
S11	126	600	130.2	0	0	84	0	0
S12	84	600	130.2	0	0	126	0	0
	Cement (gr)	Sand <5mm (gr)	Water (gr)	Superplasticizer (gr)		Dried slurry (gr)		
S13	147	600	97.6	6.3		63		
S14	105	600	97.6	6.3		105		
S15	63	600	97.6	6.3		147		
S16	168	600	97.6	6.3		42		
S17	126	600	97.6	6.3		84		
S18	84	600	97.6	6.3		126		

A comparison has also been made for the effect of various SCMs including the DCS. The mix portion of each series of mix is provided in table 5. Samples were tested against the compressive strength responses on the age of 7 days. The mini slump flow test had also conducted to illustrate the workability of each series of mix shown in table 6.

Table 5 Mix portion of different types of SCM

Cement	Sand	Water	Superplasticizer	DCS	Fly ash	Slag	Wollastonite	SF
147	600	97.6	6.3	63	0	0	0	0
147	600	97.6	6.3	0	63	0	0	0
147	600	97.6	6.3	0	0	63	0	0
147	600	97.6	6.3	0	0	0	63	0
147	600	97.6	6.3	0	0	0	0	63

Table 6 Cone drop in mini slump test [22]

DCS	1.6
Fly ash	2.3
Slag	2.2
Wollastonite	1.2
Silica fume	0.6

Compressive strength

Compressive responses of 3 samples from each mix design (Table 2) have been evaluated after 7 days of water tank curing. Average compressive strength of each mix is presented in table 3. Cubic 50x50x50 mm moulds have been selected for the purpose of this experiment. The compressive test has been carried on in accordance with the Australian standards series AS 1012, methods of testing concrete. For sample S9, as the replacement rate of the sand increased by the dried coal slurry, the workability of the concrete mortar dropped dramatically which did not allow casting of the sample.

Table 7 **Compression test results (MPa).**

	Average Compressive Strength (MPa)
S0	18
S1	13.69
S2	5.80
S3	20
S4	13.36
S5	9.08
S6	16.77
S7	13.61
S8	17.33
S9	N/A
S10	8.43
S11	4.43
S12	2.19
S13	25.82
S14	27.09
S15	29.82
S16	21.11
S17	7.48
S18	2.46

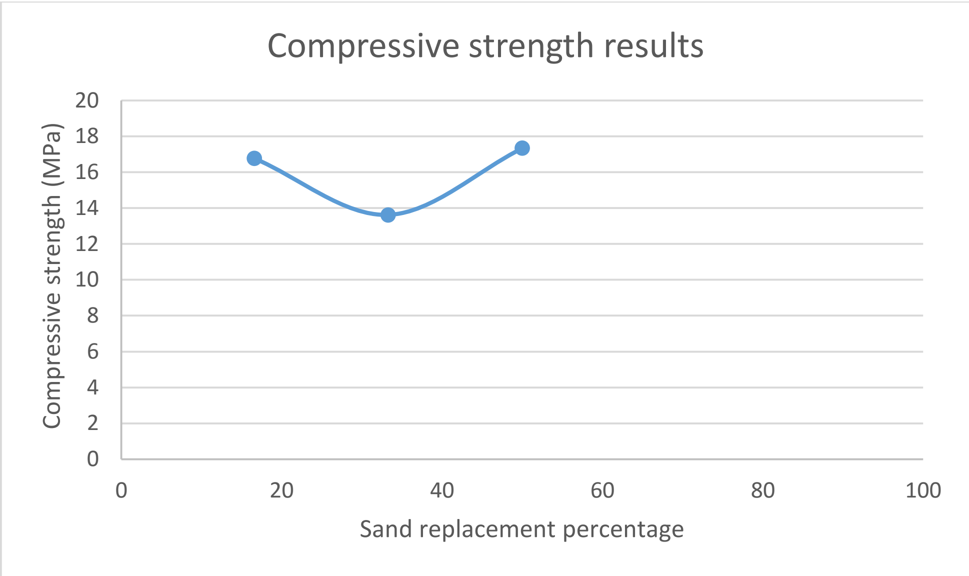

Figure 3 Effect of sand replacement by dried coal slurry on the compressive strength

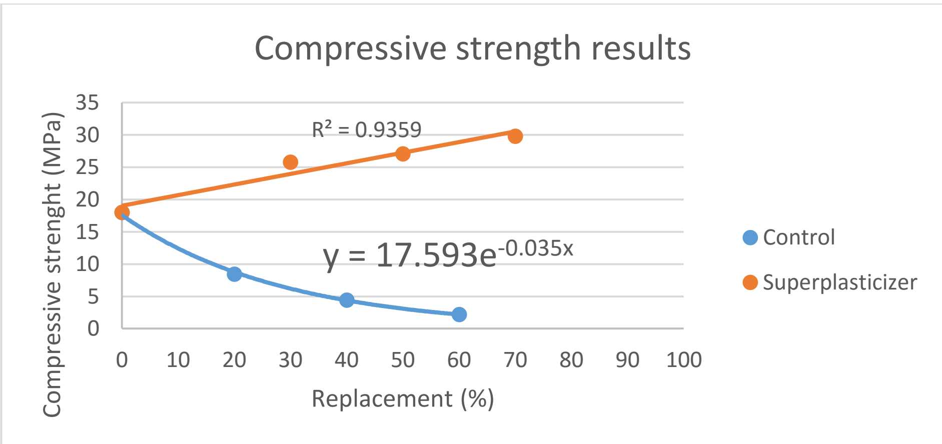

Figure 4 Comparison of cement replacement by coal slurry and the effect of superplasticiser on the compressive strength

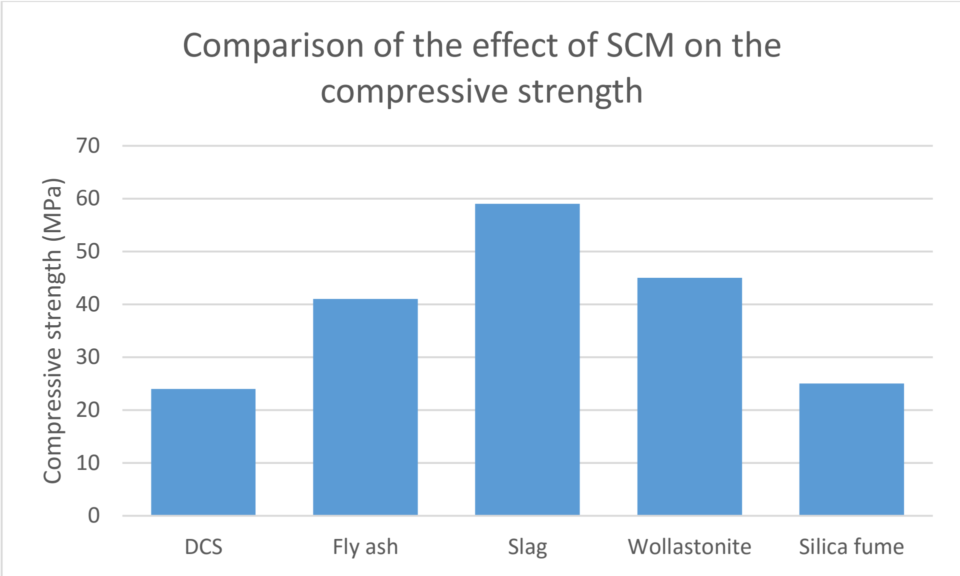

Figure 5 Compressive strength (MPa) results from the comparison of the effect of different SCM

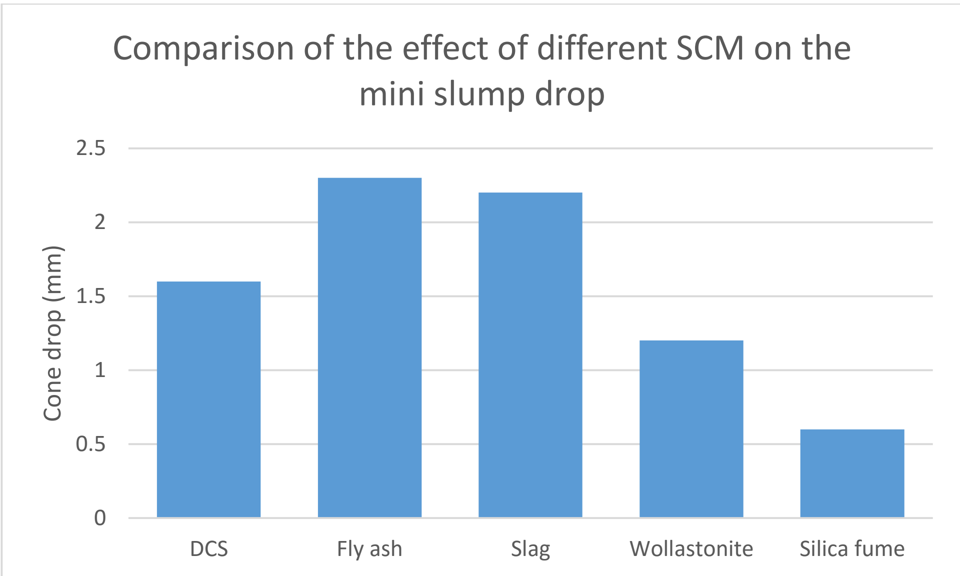

Figure 6 Comparison of the effect of different types of SCM on the mini slump drop

The concrete mortar in the hardened state leave a traces of black colour on the human skin when touched. Considering the results of chemical characterization test which indicates the existence of heavy metals and Uranium in the specific coal slurry sample used in this experiment, it is recommended for future studies to assess the elimination of the aesthetic defect and also consider the purification methods to remove the hazardous chemical elements.

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Conclusion

The study showed the feasibility of the use of coal slurry as an emerging Supplementary Cementitious Material (SCM) in concrete applications. The replacement ratio of the solid content of the coal slurry has a negative relation on the compressive strength of the concrete mortar. In other words, the result of adding more coal slurry to the concrete mix, is a lower compressive strength. However, in the presence of superplasticizer in the concrete mix, the results of the 7days compressive strength test shows a positive slope while the replacement ratio increases. The results from the comparison of the effect of various SCM on the compressive strength and the workability index indicates that the dried slurry is a well suited supplementary cementitious material amongst others. Since the treatment of the coal mining slurry is a major issue for the industry, by considering the possibility of the recycling of such waste in the construction practices along with an establishment of a close loop economy concept, a major step could be taken towards satisfying the green building approaches.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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