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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].

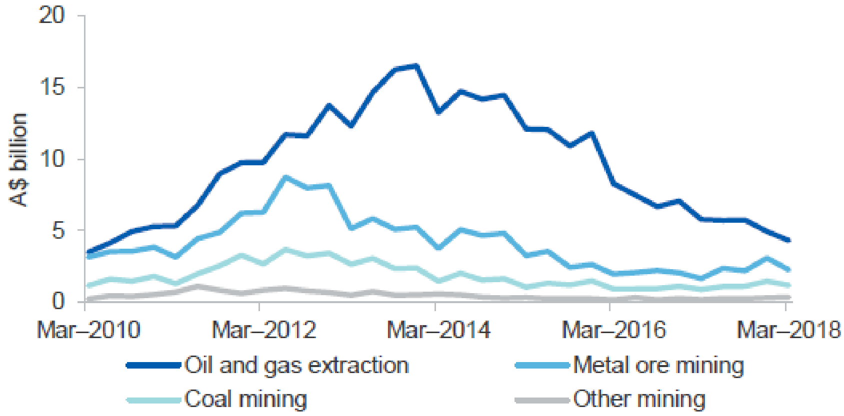

Figure 1 Australian mining capital expenditure

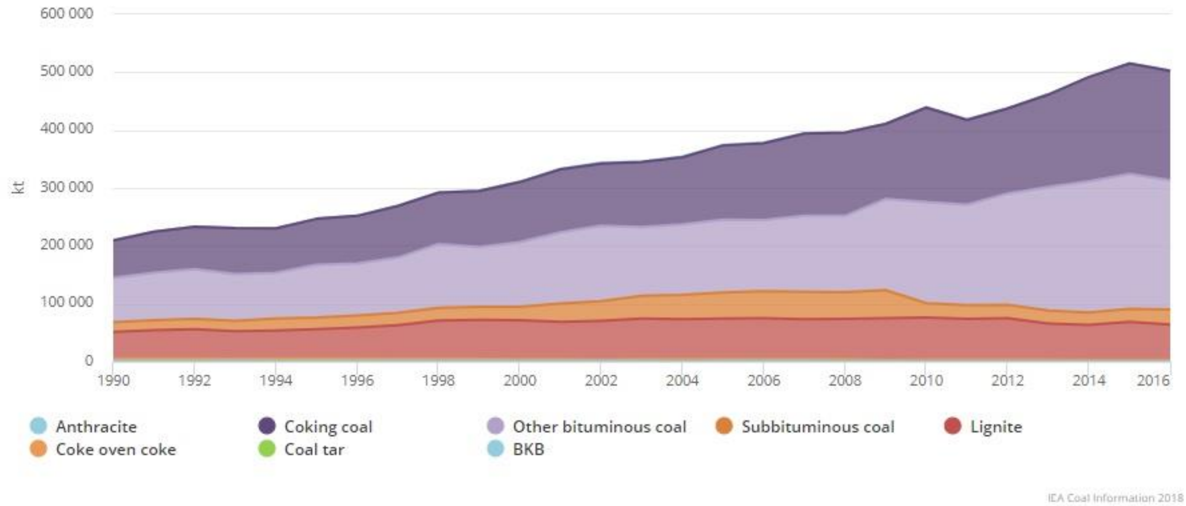

Figure 2 Coal production by type in Australia

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

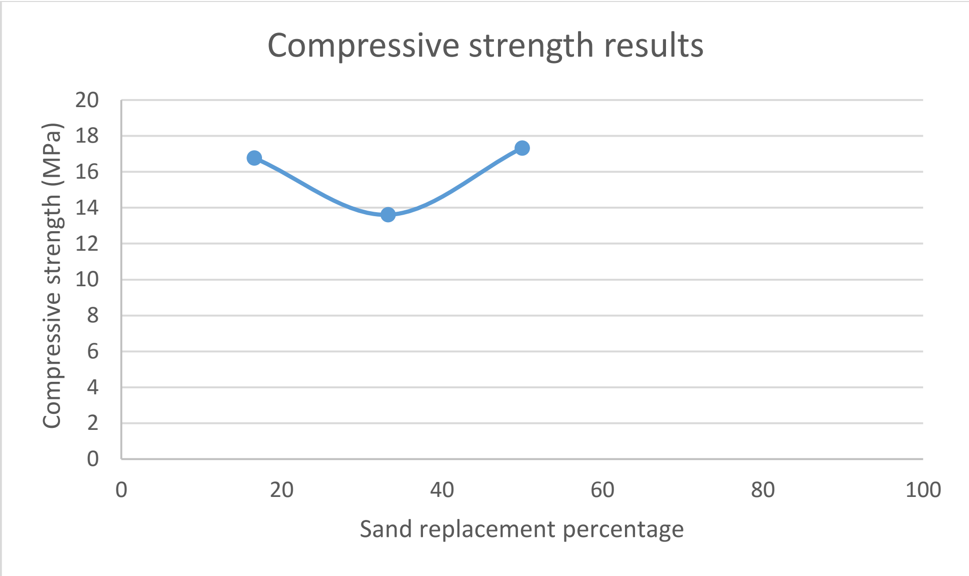

Figure 3 Effect of sand replacement by dried coal slurry on the compressive strength

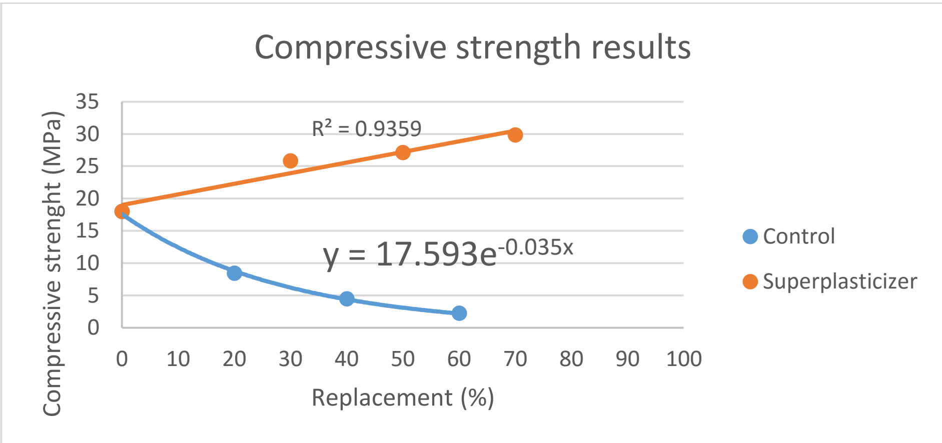

Figure 4 Comparison of cement replacement by coal slurry and the effect of superplasticiser on the compressive strength

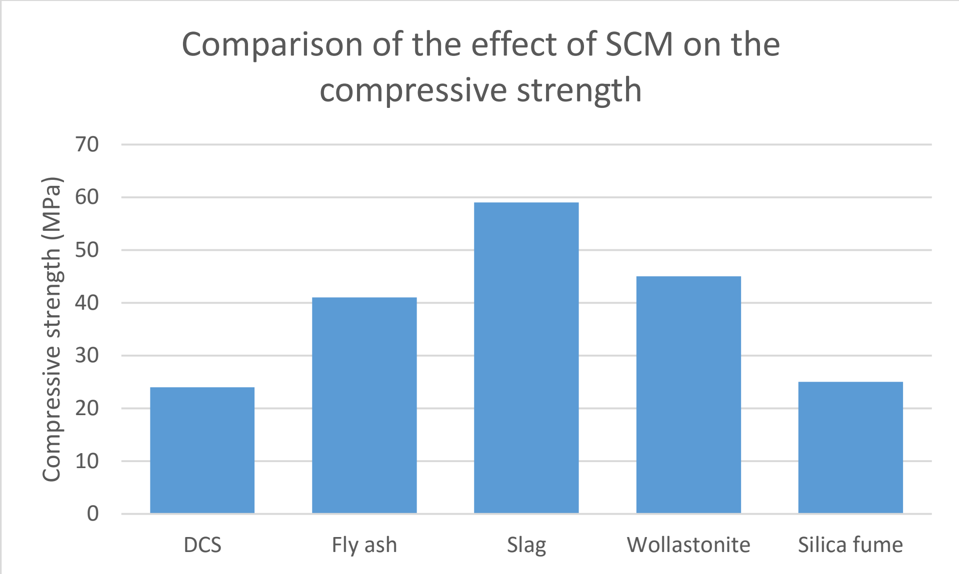

Figure 5 Compressive strength (MPa) results from the comparison of the effect of different SCM

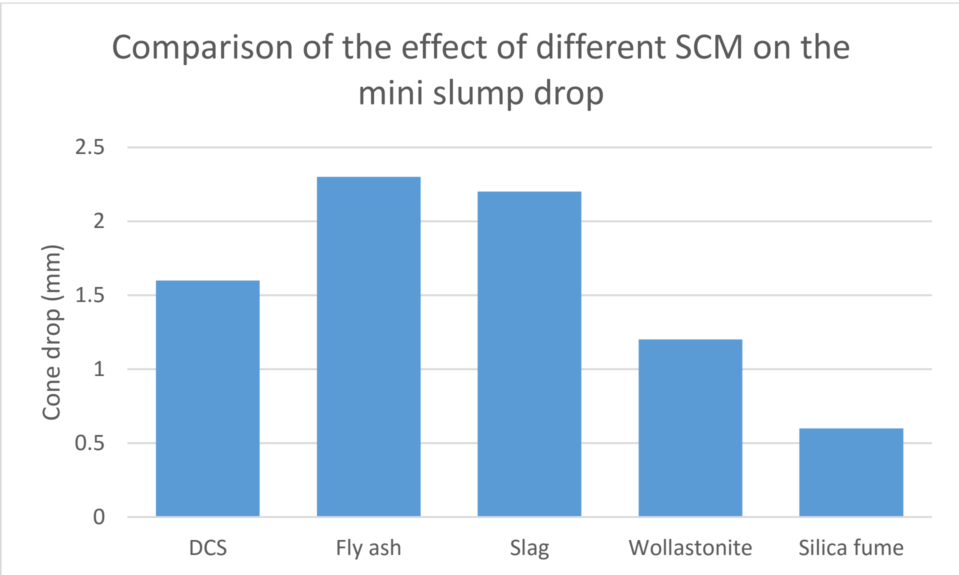

Figure 6 Comparison of the effect of different types of SCM on the mini slump drop

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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