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A Systematic Bottom-up Approach for Decarbonization of Concrete

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Abstract: Climate change is one of the biggest problems the world is facing. The Paris agreement (2015) commits signatory nations to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels. In Australia, the construction industry contributes around 18% of total greenhouse gas emissions. Australia consumes, approximately 29 million m^3 of concrete each year. The embodied carbon of structural concrete typically ranges from 230 to 615 kg CO_{2e}/m^3. On this basis, total embodied carbon associated with concrete in Australia is estimated as 12 Mt CO_{2e}. Therefore, decarbonization of concrete is a key component to Net Zero 2050 strategy across the construction industry. A typical concrete mix consists of 12% Portland cement material, 77% fine & coarse aggregates, 3% supplementary Cementitious material (SCM) and 8% admixtures/ water. Portland cement is the highest embodied carbon material (approximately 905 kg CO_{2e}/t) in a concrete mix and is responsible for approximately 90% of concrete's footprint. Most concrete decarbonization strategies propose partial or full replacement of Portland cement to reduce the carbon footprint of concrete. This paper presents an overview of a systematic analysis of various concrete decarbonization technologies being adopted worldwide. The study shows that none of the technologies can achieve the net zero goal on a standalone basis. It is recommended that a custom strategy combining more than one technology will have to be adopted to suit the circumstances.

Key words: concrete, Portland cement, carbon footprint, embodied carbon, recycled materials

1. Introduction

Climate change is one of the biggest problems the world is facing. The Paris agreement commits signatories to limit global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) has reported that there is a greater than 50% likelihood of global warming reaching or exceeding 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario. The construction industry in Australia is responsible for approximately 18% of total greenhouse gas emissions [1]. Therefore, decarbonization of this sector needs to be prioritized to achieve the Net Zero goal by 2050. Approximately 29 million m^3 of concrete is used per year in Australia with total embodied carbon (EC) of approximately 12 Mt CO_{2e}. A concrete mix typically consists of 12% to 15% of Portland cement (PC) which is responsible for approximately 90% of concrete's EC. The Portland cement replacement is therefore the focal point of most concrete decarbonization strategies.

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2. Alternative Strategies for the Decarbonization of Concrete

The pathways recommended for the decarbonization of Australian cement and concrete sector, is shown in Fig. 1, which includes decarbonization of electricity and transport (14% reduction in CO_2 footprint), use of alternative fuels (6% reduction in CO_2 footprint), innovation in concrete and cement technology (20% reduction in CO_2 footprint), innovation in design and construction (21% reduction in CO_2 footprint), carbon capture (33% reduction in CO_2 footprint) and accounting concrete re-carbonation (6% reduction in CO_2 footprint) [2]. This study envisaged that the partial replacement of PC with supplementary cementitious materials (SCM) can achieve only up to 3% reduction in concrete's EC.

It is noted that some of the recommendations such as zero emission electricity, use of green fuels, carbon capture etc. are contingent on development of new technologies and may not be feasible to be implemented in the short to medium term.

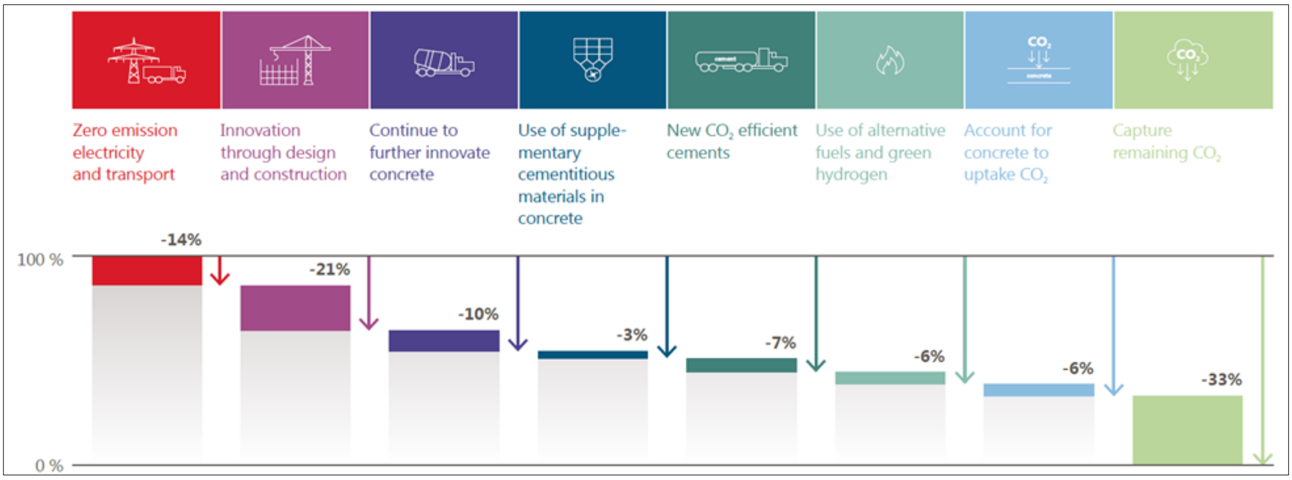

Fig. 1 Decarbonization pathways for the Australian cement and concrete sector [2].

The authors have analysed current practices of concrete application and various technologies that can be adopted to accelerate decarbonisation of concrete in short to medium term, as presented in Fig. 2. This figure outlines the key decarbonization strategies for concrete, including:

Legend: Black Text: Current Practices and Red Text: Recommended Practices

Fig. 2 Alternative strategies for decarbonization of concrete in Australia.

- Decarbonisation of cement by optimising the fuel related carbon emissions by including green fuels such as ethanol and hydrogen in alternative fuels already being used for replacing the fossil fuels.
- Increasing the uptake of supplementary cementitious materials (SCM) for replacing the PC in concrete mixes, both by increasing the cement replacement level and augmenting the conventional SCMs, fly ash, ground granulated iron blast-furnace slag (GGBFS) and silica

fume (SF) with new SCMs such as calcined clay.

- Increasing uptake of zero PC concrete such as geopolymer concrete, sulphur concrete to replace PC concrete where feasible.
- Deploy CO_2 curing in place of current practice of water and steam curing to recycle CO_2.
- Deploy high strength and ultra-high strength concrete in place of standard concrete mixes to for reducing the cross-sectional area and weight of the structural elements inter alia overall material consumption.

3. Decarbonization of Calcination Process Fuel

It is reported that approximately 26% of CO_2 emissions relating to the calcination process of cement production in Australia is attributed to the fuels [2]. The authors [3], after a detailed modelling determined that by using regenerative fuels including biomass, waste timber and ethanol, and waste stream materials such as end-of-life tyres and residual oil in the short to medium term (whilst green fuels such as hydrogen are being developed), the fuel related CO_2 emission, may be reduced by up to 12.5%. It was recommended that in the long-term a combination of hydrogen, ethanol and residual oil may be adopted for up to 61.5% reduction of fuel related emission. This equates to up to a 1.3% reduction in global cement industry related CO_2 emission, as shown in Fig. 3.

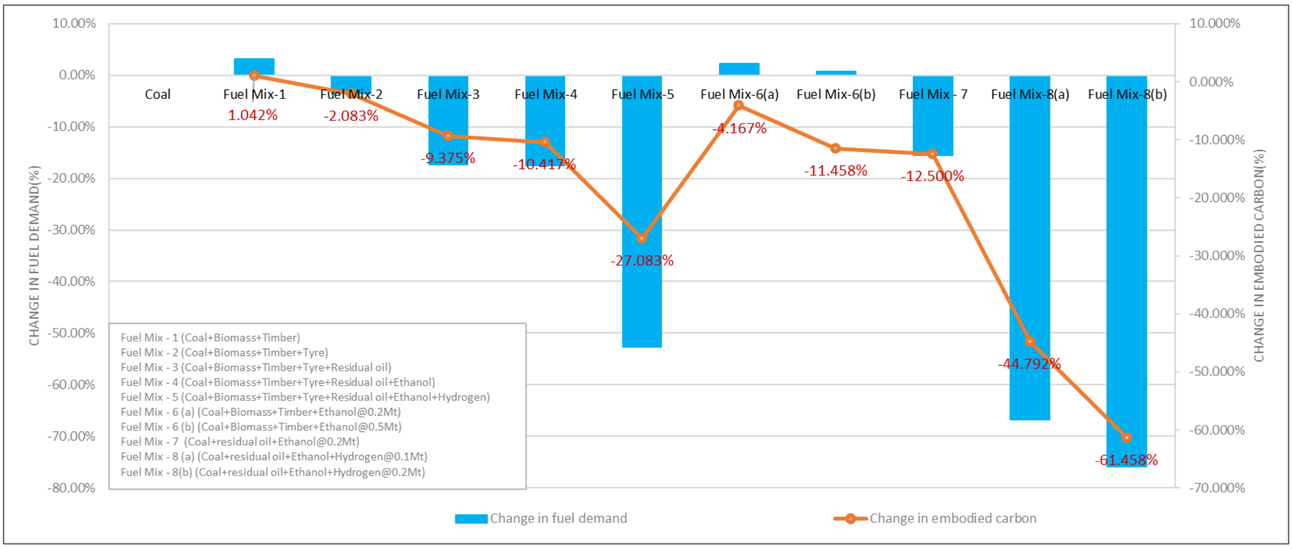

Fig. 3 Effect of adding alternative fuels on fuel demand and embodied carbon [3].

4. Partial Replacement of Portland Cement

Only production stage emission (Scope A1 to A3) has been considered for determining the effectiveness of partial/full replacement of PC in decarbonization of concrete. AusLCI database [4] has been used for calculating EC of concrete mixes in the present study. Australian Technical Infrastructure Committee (ATIC) specification Section SP43 — cementitious materials for concrete [5], which is being widely followed for specifying structural concrete, allows use of fly ash, ground granulated iron blast-furnace slag (GGBFS) and silica flume as binary and ternary blend for replacing the Portland cement. The maximum percentage of SCM allowed by ATIC-SP43 in binary and ternary blends along with its effect of concrete's EC is given in

Table **1**. This analysis shows that for a 40 MPa concrete mix with binder content of 400 Kg/m^3, the concrete's EC may be reduced by up to 59% if PC is replaced with SCMs full permissible values.

In Australia, concrete suppliers are already supplying the low carbon concrete (LCC) for structural applications (including bridge construction) with high degree of PC replacement with SCMs, some examples are given below:

- Envisia: > 50% reduction in Portland Cement; EC = 234 kg CO_{2e}/m^3 for 40 MPa concrete [6].
- Ecotera: 55% reduction in Portland Cement; EC = 247 kg CO_{2e}/m^3 for 40 MPa concrete [7].
- Futurecrete® Ultra: up to 65% reduction in Portland Cement; EC = 287 kg CO_{2e}/m^3 for 40 MPa concrete [8].

Table 1 EC reduction of SCM concrete mixes due to ATIC SP43 [5] permissible limits.

Cementitious binder blend		Maximum Mass (%)		Estimated EC reduction for S40 concrete with binder of 400 kg/m^3 (EC = 362 kg CO_{2e}/m^3)
SCM I	SCM II	SCM I	SCM II	
Fly Ash	-	40	-	-39.12%
GGBFS	-	70	-	-55.30%
Silica Fume	-	10	-	-9.85%
Fly Ash	Silica Fume	30	4	-33.28%
GGBFS	Silica Fume	50	4	-43.44%
GGBFS	Fly Ash	50	20	-59.06%

5. Full replacement of Portland Cement

Several concrete technologies with alternative binders, including geopolymer concrete (GC), Sulphur concrete (SC), Lime Calcined Clay Concrete (LC^3) etc. are being developed/trialed for replacing the Portland cement (PC), as given below.

- **GC** binder is formed by the interaction of an alkaline solution (activating solution or activator) with a reactive aluminosilicate powder such as fly ash, GGBFS etc. This binder, when mixed with coarse and fine aggregates, produces a high performance low-CO_2 concrete. The EC of GC binder is up to 80% lower than PC [9]. Austroads Technical Report AP-T329-17 [10] envisaged that a typical 40 MPa compressive strength GC consists of 60% fly ash, 40% GGBFS and 12.5% alkali activator (sodium meta-silicate pentahydrate). It is estimated that the EC of this mix will be 77.52% lower than PC concrete of similar strength. In Australia, GC is being trialed and has been used to a limited extent e.g. Salmon Street Bridge over West Gate Freeway, Wagner's Wharf on the Brisbane River, Pavement, barriers, kerb and bridge at Wellcamp Airport, etc.
- **SC** is produced by replacing water and PC in the concrete mix with Sulphur binder. ACI 548.2R-93 [11] provides a detailed guideline for mixing, placing, transportation and installation of SC. SC may be produced by mixing aggregates heated to 177 to 204°C with modified sulfur cement and fine mineral filler to prepare a uniform, well mixed concrete that is then maintained within a temperature range of 132 to 141°C until placement. SC exhibits superior mechanical and durability properties as compared to PC concrete [12], as shown in Fig. 4. This figure stipulates that SC has superior mechanical strength properties including rapid strength gain (55-65 MPa compressive strength in 3 hours), modulus of elasticity (50 GPa), flexural strength (16 MPa), etc. SC also has excellent durability properties including chloride, freeze-thaw and chemical resistance making it an excellent building material for construction of structures subjected to corrosive environment such factory floors, chemical tanks, drains/sewer, maritime structures, bridge decking subjected to freezing/thawing, etc. SC may not be suitable for constructing load bearing structural elements requiring fire resistance because

Sulphur softens when exposed to a temperature >100°C. EC of SC is likely to be significantly lower than PC concrete because SC requires heating only up to 204°C for mixing, transportation, and installation process. SC can be fully recycled recyclable at the end of the life by reversing the manufacturing process. SC may therefore be considered as a part of the solution for decarbonization of concrete. SC is not being commonly used in Australia.

- **LC^3** is manufactured by partially replacing clinker with calcined clay and limestone. It is reported that clays containing about 40% kaolin or above give strengths comparable to PC concrete when used in LC3-50 (50% clinker, 30% calcined clay, 15% limestone and 5% gypsum) [13]. LC^3-50 concrete provides good mitigation of alkali silica reaction (ASR) with reactive aggregates and lower chloride diffusion coefficient and good sulphates resistance. LC^3-50 concrete provides carbonation resistance comparable to other blended cements. LC^3 is considered as an alternative to conventional SCMs.

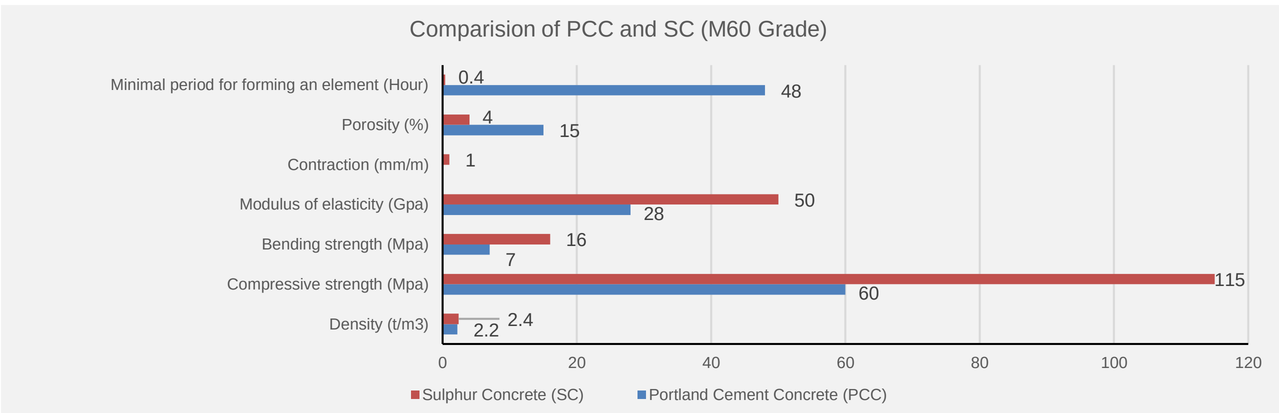

Fig. 4 Mechanical and durability properties of M60 grade cement and sulfur-based concrete [12].

6. CO_2 Recycling in Concrete

Addition of an optimum dose of liquid CO_2 in ready mixed concrete during batching process results in the formation of mineralized calcium carbonate ($CaCO_3$) due to the reaction of CO_2 with freshly hydrated cement forming calcium carbonate and calcium silicate hydrate gel storing the CO_2 permanently in the concrete. The process flow is shown in Fig. 5. It is reported that when CO_2 @ 0.06% by weight of cement is injected in a concrete mix (design 28 days compressive strength of 48.2 MPa) comprising a ternary blend binder comprising of cement (50%), slag (37%) and fly ash (13%), resulted in a cement reduction of 55 kg/m^3 (20%) for similar mechanical properties of concrete and a 1% greater 7 days and 3% greater 28 days compressive strength of the concrete [14]. This technology provides dual benefit viz. enables recycling of CO_2 sourced from flue gases and also replaces the PC in a concrete mix similar to SCMs. This technology is not being commercially used in Australia.

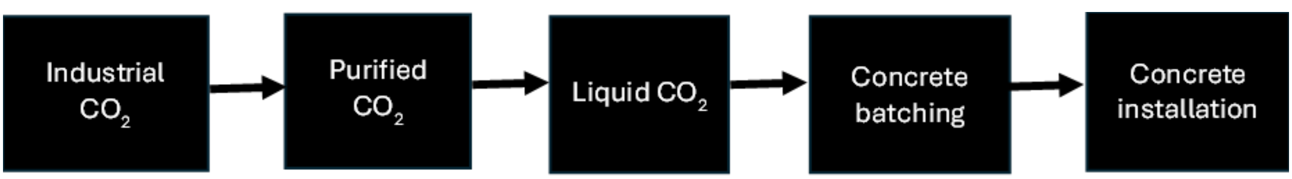

Fig. 5 CarbonCure process [14].

7. Use of Ultra-High Strength Concrete (UHPC) for De-Materialization

UHPC is concrete that has a minimum specified compressive strength of 150 MPa [15]. UHPC typically UHPC typically consists of cement, silica fume, fine quartz sand, high-range water-reducing admixtures, and fibers. The water-binder ratios for UHPC usually range between 0.15 and 0.25. The compressive strength, tensile strength, and elastic modulus (E) of UHPC varies from 150 to 250 MPa, 6 to 12 MPa, and 40 to 50 GPa, respectively. Since parameter EI (I = moment of inertia) governs the cross-sectional dimensions of a structural element. It is envisaged that the sectional area of a structural member may be reduced by up to 50% by using UHPC, leading to significant reduction in material consumption. It is reported that the span of a bridge girder may be doubled by using UHPC girders with only 50% additional weight [16]. This will reduce material use and carbon footprint of the project. UHPC has been used in Australia to a limited extent, one of the examples is Shepherds Creek Road Bridge.

8. Conclusion

From the above analysis it is concluded that partial and full replacement of PC in concrete alone will not be able to achieve Net Zero objectives. Further innovation in design and construction methodology is required for reducing EC and operational emission. Technologies for recycling CO_2 emitted from various processes in concrete need to be developed to help decarbonization of concrete. It is concluded that no single concrete decarbonization technology can achieve the Net Zero objective and a combination of various strategies customized for a project will need to be deployed.

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