# INTERIM TECHNICAL REPORT

**NACOE P58: Alternative Cementitious Binders for Cost-effective and Sustainable Transport Infrastructure – Biochar (2025–26)**

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# Summary

This study evaluated the potential of using biochar as a replacement for fine aggregate (sand) in concrete for Queensland's transport infrastructure. Cement and concrete are major contributors to embodied emissions in Queensland Department of Transport and Main Roads (TMR) projects, and biochar offers opportunities to reduce the overall carbon footprint of concrete and, thus, support the Queensland Government's Net Zero targets under the *Clean Economy Jobs Act 2024*.

Research indicates that biochar's performance in concrete mainly depends on feedstock type, pyrolysis conditions and the level of replacement of the fine aggregate. At low replacement levels (typically < 20% by volume or < 5% by weight), biochar can maintain or even improve the compressive and flexural strength of concrete due to internal curing effects. However, higher levels of replacement generally reduce strength and/or durability due to the increased porosity in the matrix and weaker particle bonding. Biochar incorporation consistently reduces density and can improve thermal and acoustic insulation. Some studies have also reported benefits such as reduced shrinkage and enhanced chloride resistance. However, the high water absorption and increased void content raise concerns about long-term durability, of which there is little or no knowledge in the current literature. Most evidence that is available is from small-scale laboratory investigations, with only one Australian field trial to date.

From a compliance perspective, biochar does not currently meet MRTS70:2022 or AS 2758.1:2014 requirements for fine aggregate. Challenges include very low particle density, high water absorption and the potential exceedance of chloride and organic impurity limits. Durability properties (sulphate loss, degradation factor and alkali silica reactivity (ASR)) have also not been tested.

Overall, biochar shows some potential at low levels of replacement of the fine aggregate component of a concrete mix for low risk non-structural N class concrete applications where reduced density and associated functional benefits are of value. However, some significant further testing is required to address compliance and durability/structural performance gaps before biochar can be considered a viable option for use in TMR N and S class structural concrete applications. At this point in time, there appears to be no economically viable or scalable source of biochar material in Queensland to justify or support any further potential research or development for its use in concrete. This may change in the future.

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# 1 Introduction

## 1.1 Background

This desktop study aimed to investigate the potential for using biochar as a fine aggregate replacement to lower the carbon footprint in concrete used in the construction of Queensland's transport infrastructure. This assessment aligns with efforts to explore emerging material technologies for concrete manufacturing and supports the Queensland Government's legislated Net Zero targets under the *Clean Economy Jobs Act 2024*.

## 1.2 Scope

This report presents a high-level feasibility assessment of biochar as a fine aggregate (sand) replacement in concrete. The assessment included:

- a high-level desktop review, comparing to Queensland Department of Transport and Main Roads (TMR) MRTS70 specification and considering the practical aspects of its utilisation
- a feasibility/viability/suitability determination (proceed/do not proceed) for the product.

## 1.3 Report Structure

The report is structured as follows:

- Section 2 summarises the material characteristics of biochar and the findings from some international studies on its use as a fine aggregate in concrete.
- Section 3 evaluates the compliance of biochar with relevant TMR specifications.
- Section 4 provides the discussion and conclusions.

# 2 Literature Review

Biochar is produced by heating biomass under limited or no supply of oxygen, a process known as pyrolysis, resulting in a carbon-rich material. A wide range of feedstocks can be used in producing biochar, including forestry by-product, food waste, crop residue and municipal solid waste (MSW). Biochar is considered a promising $CO_2$ sequestration and storage medium as it locks the atmospheric $CO_2$ into a stable form, preventing its release through decomposition. Because it removes more $CO_2$ than it emits across its life cycle, biochar is often claimed as a carbon-negative product (Akinyemi & Adesina 2020) and, therefore, can be used to effectively reduce the overall carbon footprint when incorporated into other materials such as concrete.

Biochar has been utilised in several applications such as soil amendments in agriculture; adsorbents for water and air pollutants; and catalysts in biofuel production, biogas upgradation and construction materials (Senadheera et al. 2023). When used in the construction field, biochar can reduce embodied carbon by partially replacing carbon-intensive materials such as cement and natural aggregate, while also enabling structures to act as long-term carbon sinks. However, the technical performance of biochar incorporated into construction materials must be rigorously evaluated before large-scale adoption. This literature review focuses on using biochar as a fine aggregate replacement in concrete.

## 2.1 Material Characteristics of Biochar

The material characteristics of biochar, such as size, shape, density, morphology, pore structure and element composition, depend on the feedstock type and pyrolysis conditions, with more details available in the review papers by Akinyemi and Adesina (2020), Senadheera et al. (2023) and Sun et al. (2025).

The primary elements of biochar are carbon (C), hydrogen (H) and nitrogen (N), which together account for more than 95% of its weight. It also contains inorganic elements such as calcium (Ca), magnesium (Mg), sulphur (S), potassium (K), sodium (Na), phosphorous (P), aluminium (Al), silicon (Si) and chloride (Cl) (Senadheera et al. 2023). Some biochar may contain heavy metals, so from an environmental perspective, it is important to avoid selecting feedstocks with concerning levels of heavy metals (Yang et al. 2019).

Biochar typically exhibits a highly porous structure, which can enable it to act as an internal curing agent when incorporated into cementitious composites such as concrete. The pores retain water and gradually release it during cement hydration, thereby facilitating strength gain and durability development (Gupta & Kua 2018).

## 2.2 Biochar As Fine Aggregate

The majority of the existing studies on biochar have focused on using it as a cement replacement. The optimum replacement dosage has been concluded to be up to 3% by weight, beyond which the mechanical performance of mortar/concrete would be significantly compromised (Sun et al. 2025).

The literature review identified 11 studies that assessed the feasibility of using biochar as a fine aggregate replacement. These studies are categorised by feedstock type and discussed in detail below.

### 2.2.1 Waste Coffee Grounds

Roychand et al. (2023a) investigated the feasibility of using biochar derived from spent coffee grounds (SCG) as a partial sand replacement at 5, 10, 15 and 20% by volume. The SCG were sourced from local cafes and pyrolysed at laboratory scale at 2 temperatures, 350 °C and 500 °C. The resulting biochar had specific gravities of 0.30 (350 °C) and 0.265 (500 °C). Elemental analysis showed sulphur contents of 0.50 ± 0.07 and 1.30 ± 0.10% by weight and chlorine contents of 0.15 and 0.04% by weight for the 350 °C and 500 °C biochar, respectively. The biochar particles were finer than natural sand used in this study. When the 350 °C biochar was used, the 7-day compressive strength was lower than the control at all replacement levels, but the 28-day compressive strength increased with increasing replacement, with 15 vol.% identified as the optimum level with a 29.3% enhancement compared to the reference group (29.6 MPa vs 22.9 MPa). Even at 20 vol.% replacement, the strength remained comparable to the control with only a minimal reduction. The authors attributed the strength enhancement to the internal curing effect of the porous microstructure of the concrete incorporating the biochar and to the cement penetrating biochar providing a denser microstructure. In contrast, concrete containing the 500 °C biochar exhibited a continuous reduction in compressive strength with increasing replacement level, with a 34.5% decrease at 15 vol.% replacement. This was attributed to the weakening of the biochar skeleton at higher pyrolysis temperatures, where excessive porosity and micro-cracking compromised the cement microstructure.

Roychand et al. (2025) conducted a field trial (concrete footpath) in Victoria, Australia, using the identified optimum pyrolysis temperature of 350 °C and optimum replacement level of 15 vol.% in an N25 concrete with a target slump of 80 mm. The coffee biochar used in this trial was produced at an industrial level, but at 450 °C due to the limitations of the industrial pyrolysis reactor. The biochar concrete had a higher slump than the control concrete (75 mm vs 65 mm). The authors attributed this behaviour to a lubricating effect caused by the quenching process during biochar production and to the gradual water release from the wet biochar acting as a reservoir. They suggested that oversaturated biochar may provide better workability control. In terms of mechanical performance, the biochar concrete showed ~6% and ~9.3% lower compressive strength than the control mix at 7 days (20.5 MPa vs 21.8 MPa) and 28 days (28.3 MPa vs 35.5 MPa), respectively. However, the 54-day compressive strength of cored biochar concrete samples slightly exceeded that of the control concrete (33.0 MPa vs 32.5 MPa), indicating that the additional water in the biochar may have promoted further cement hydration. The biochar concrete also showed 18.9% higher flexural strength than the control concrete at 28 days and a better shrinkage performance.

### 2.2.2 Waste Wood Biochar

Wang et al. (2020) investigated waste wood–derived biochar as a partial sand replacement in mortar at 1, 2 and 5% by weight, using laboratory pyrolysis at 500 °C and 700 °C. The feedstock had the same particle size range as the sand, and the biochar was used in surface saturated dry (SSD) condition. At 1% by weight replacement level, compressive strength increased by 8 to 10% due to enhanced cement hydration, but higher replacement levels reduced the strength because of the biochar's porosity and brittleness. The authors noted that performance depends on balancing the positive internal curing effect with negative pore enlargement. Biochar produced at 700 °C outperformed that at 500 °C, as its larger pores and surface area retained more water. The optimum performance was achieved with 1 wt.% replacement using 700 °C biochar.

Chen et al. (2022) incorporated wood biochar, derived from waste wood at a Hong Kong farm, into dry mix concrete partition blocks as a fine aggregate replacement at 10, 20 and 30% by weight. The biochar was sieved to 0 to 5 mm to match the particle size of fine aggregate. It had a water absorption of 83.6% and was pre-soaked to SSD condition before use. The compressive strength decreased with increasing replacement, as the negative effect of higher porosity outweighed the benefits of internal curing. Strength reductions of 5%, 10% and 35% were observed at 10%, 20% and 30% by weight replacement, respectively.

Roychand et al. (2023b) investigated waste wood–derived biochar as a partial sand replacement at 10, 20 and 30 vol.%. The biochar was sourced from a local company, and it had a specific gravity of 0.45, water absorption of 70% and a coarser particle size than the sand used. Sulphur and chlorine contents were 0.02 ± 0.01% by weight and 0.72% by weight, respectively. At all replacement levels, the biochar concrete showed higher 7-day and 28-day compressive strengths than the control concrete, except for the 7-day strength at 30% by volume replacement, which was slightly lower. The optimum level was reported to be 20% by volume, yielding 63.9% and 20.1% higher 7-day (27.9 vs 19.1 MPa) and 28-day (37.7 vs 30.8 MPa) compressive strengths, respectively. The authors attributed the strength performance to the balance between the internal curing effect of the biochar and its relatively weak inherent strength.

Liu and Li (2025) produced biochar from waste bamboo in the laboratory and used it to replace fine aggregate in concrete at 10, 20 and 30% by volume. The bamboo biochar matched the particle size range of the fine aggregate and was pre-soaked before use. The compressive strength increased with the replacement level, showing strength increase of 9.2% (35.7 MPa), 15.9% (37.9 MPa) and 17.7% (38.5 MPa) compared with the control (32.7 MPa). The superior performance may be attributed to the higher structural hardness of bamboo biochar relative to other feedstocks. Thermal conductivity was found to decrease with the increasing replacement levels, as the heat exchange is isolated by the connecting pores inside bamboo biochar indicating enhanced heat insulation. The ion penetration resistance was also improved due to the densification of the concrete matrix with the addition of biochar.

### 2.2.3 Food and Agricultural Waste

Cuthbertson et al. (2019) used biochar produced in the laboratory from dried distiller grains to replace either sand or coarse aggregate in concrete at 1 to 15% by weight replacement. They observed a linear relationship between biochar content and the additional water required to maintain workability. Hardened density decreased proportionally with increasing biochar, while both sound and thermal insulation were improved. No adverse effects on compressive strength were reported up to 3% by weight replacement.

Praneeth et al. (2021) produced biochar in the laboratory by pyrolysing poultry litter, further modified with bentonite clay, formic acid and basalt dust. The biochar particle size distribution was comparable to cement and a sulphur content below 0.3 wt.%. Sand was replaced with biochar in mortar at 10, 20 and 40 wt.%. Compressive strength decreased with higher replacement, showing reductions of 21%, 30% and 42% at 10%, 20% and 40 wt.% respectively. The authors attributed the strength reduction to a more porous matrix, weaker bonding and additional water added during mixing. In contrast, flexural strength improved, with a maximum 26% increase at 20% by weight due to matrix refinement, but it declined at higher dosages due to the excessive porosity. Water absorption and void content increased with replacement, reflecting the high porosity and water retention capacity of biochar. Thermal conductivity dropped by 26% at 10% by weight but increased at higher contents, becoming 10% higher than the control at 40% by weight, suggesting that biochar initially enhances insulation, but excessive addition creates more conduction pathways.

Maljaee et al. (2022) produced biochar from waste olive stone in the laboratory and used it to replace 25, 45 and 60% by volume of the coarse sand fraction (> 1 mm) in mortar. The biochar had a particle density of 1.635 and a chlorine content of 0.1% by weight. With increasing replacement, fresh and hardened densities decreased linearly due to the low density and high porosity of biochar, with reductions of 15% and 13% at 60% by volume. Water absorption also increased linearly, reaching a 60% rise at 60 vol.% replacement, reflecting the more porous matrix. Compressive strength decreased at all levels, by 7 to 11% at 7 days and 15 to 22% at 28 days. The reduction was attributed to the porous nature of biochar. However, sound and thermal insulation were improved with biochar incorporation.

Chen et al. (2024) produced biochar from food waste digestate by laboratory pyrolysis at 550, 650 and 750 °C for use as aggregate in lightweight concrete blocks. The resulting biochar products had water absorption of 45.1 to 49.5% and sulphur contents of 0.7 to 1.7 wt.%. The concrete blocks incorporating 750 °C biochar achieved a 28-day compressive strength of 57.8 MPa and a density of 1,770 kg/m³, meeting the requirements for high-strength lightweight concrete.

Tang and Qiu (2024) developed a lightweight non-structural concrete (5.5 MPa) using reactive magnesia cement and high-volume biochar, comprising 61 vol.% of the mix. The biochar was produced industrially from peanut shells, sieved to < 1 mm and used in SSD condition. The study focused on $CO_2$ sequestration from ambient air, finding that biochar enhanced the carbon uptake of the concrete during the service stage. Wang et al. (2021) also reported an accelerated carbonation process with the addition of biochar.

### 2.2.4 Municipal Solid Waste (MSW)

Mrad and Chehab (2019) investigated the use of biochar derived from MSW, sourced from a plant in Lebanon, as a sand replacement in mortar at 5, 10, 15, 25 and 45% by weight. The biochar was coarser than sand and had a specific gravity of 0.668. The water absorption was 60%, which is lower than other internal curing agents according to the authors. It was pre-soaked to SSD before use. Compressive strength decreased with increasing replacement level. The authors suggested 10% by weight with pre-soaking as the optimum approach, as reductions were significant at higher levels. Strength reduction was about 20% below 10% by weight replacement but increased to 60% at 15% by weight and 77% at 25% by weight. Additionally, a greater strength reduction was observed under water curing when compared to air curing, since additional water uptake reduced the benefits of internal curing.

### 2.2.5 Summary

Among the 11 reviewed studies, approximately half used laboratory-produced biochar and the remainder used industry-produced biochar. Except for the coffee biochar studies, which progressed to a field trial in Australia, almost all investigations were conducted at the laboratory scale. The coffee biochar study highlighted that industrial pyrolysis processes may not reproduce the optimum pyrolysis conditions identified under laboratory settings. Overall, this indicates that the application of biochar as a fine aggregate replacement remains at a very early stage, with limited evidence on its scalability and feasibility for widespread implementation.

The reviewed studies also demonstrate that the performance of biochar as a fine aggregate replacement in concrete is dependent on the feedstock type, pyrolysis conditions and replacement amount. The following is a summary of the findings:

- Density: Across all feedstocks, biochar incorporation reduced concrete density (where reported) due to its inherently low particle density, contributing to the development of lightweight concrete products.
- Workability: In most studies, biochar was used in oversaturated or pre-soaked condition, and detailed effects on workability were not extensively reported. An increase in slump was observed for oversaturated coffee biochar concrete in a field trial and suggested oversaturated biochar may provide better workability control. If biochar is introduced below SSD condition, a reduction in workability can be expected due to its high water absorption.
- Compressive strength: Although feedstock type and pyrolysis conditions directly affect performance, most studies indicate that low replacement levels (typically < 20% by volume or < 5% by weight) can achieve improved, or at least comparable, compressive strength. The effect on strength is generally governed by a balance between the beneficial internal curing effect of biochar and the negative influence of its inherently weak particles, and the increased matrix porosity that is introduced.
- Flexural strength: Improvements were sometimes observed at intermediate dosages in 2 studies. This enhancement has been attributed to matrix refinement and improved stress transfer from the cement paste to the biochar-filled voids. However, at higher replacement levels, excessive porosity and weak bonding of biochar particles dominated, leading to strength reductions.
- Functional properties: Biochar addition enhanced sound and thermal insulation across multiple studies, making it attractive for non-structural and lightweight applications.
- Durability properties: Improved shrinkage performance and enhanced chloride resistance were reported in individual studies. However, water absorption and void content consistently increased with higher biochar contents reported by several studies, which may compromise long-term durability. There is a knowledge gap in the understanding of the long-term performance of biochar-modified concrete.

# 3 Comparison to current specifications in Queensland

In this section, the potential suitability of using biochar as a fine aggregate in concrete is assessed against current relevant specifications in Queensland. MRTS70:2022 Clause 7.5.1 stipulates that ‘aggregate shall conform to AS 2758.1 unless specified otherwise’. Table 3.1 compares the properties of biochar (from the reviewed studies) against the AS 2758.1 requirements. While there are some additional requirements in MRTS70 for fine aggregate, this section only concentrates on the requirements of AS 2758.1 to gain an indication of suitability.

**Table 3.1: Properties of biochar (from the reviewed studies) against AS 2758.1 requirements**

| Properties | AS 2758.1 requirements | Biochar (from reviewed studies) | Implication |
|---|---|---|---|
| **General requirements** | | | |
| Particle density | 2.1–3.2 $t/m^3$ (Normal weight) | 0.26–0.85 $t/m^3$ across all feedstocks, which will be classified as either ‘lightweight aggregate’ or ‘Ultra lightweight aggregate’ | May float or segregate during mixing and placement |
| | > 3.2 $t/m^3$ (Heavyweight) | | |
| | 0.5–2.1 $t/m^3$ (Lightweight) | | |
| | < 0.5 $t/m^3$ (Ultra lightweight) | | |
| Bulk density | < 1.2 $t/m^3$ (Lightweight) | Not reported | More investigation required |
| Water absorption | Can exceed 2% for lightweight, vesicular or recycled aggregate considerably without affecting many of the properties of concrete made using such aggregates | 45–80% across all feedstocks | Pre-wetting required; challenges in material storage |
| **Dimensional requirements** | | | |
| Particle size distribution | Recommended envelope | Various particle size distribution reported. In most studies, the particle size was deliberately controlled (by sieving) to match the grading of natural sand or fine aggregate | May be achievable with controlled processing, meaning additional production steps and costs |
| Material less than 0.075 mm | < 20% for manufactured fine aggregate | Not reported | Processing dependent, there is a risk of excessive fines |
| Deleterious fines index | ≤ 150 | No reported testing in literature | More investigation required |
| **Durability** | | | |
| Sodium sulphate loss | ≤ 6% for all exposure classifications | No reported testing in literature | More investigation required |
| Degradation factor | ≥ 60 for all exposure classifications | No reported testing in literature | More investigation required |
| **Alkali-reactive materials** | | | |
| Aggregate reactivity classification | Non-reactive: < 0.1% at 21 days | No reported testing in literature | More investigation required<br>Expected to be considered as low risk for alkali silica reactivity based on its composition |
| | Slowly reactive: < 0.1% at 10 days or ≥ 0.3% at 21 days | | |
| | Reactive: ≥ 0.1% at 10 days or 0.1–0.3% at 21 days | | |

| Properties | AS 2758.1 requirements | Biochar (from reviewed studies) | Implication |
|---|---|---|---|
| **Impurities** | | | |
| Organic impurities | No darker than the reference (tested as per AS 1141.34) | No reported testing in literature | More investigation required<br>May fail the test as biochar is carbon-rich and black and may leach colour |
| Sugar | No trace (tested as per AS 1141.35) | No reported testing in literature | More investigation required<br>Incomplete decomposition (poor pyrolysis) of sugar in the original biomass could fail the test |
| Chlorides (Cl) | ≤ 0.04% (determined as per AS 1012.20.1) or 0.03% (determined as per AS 1012.20.2) (reinforced concrete)<br>≤ 0.15% (determined as per AS 1012.20.1) or 0.12% (determined as per AS 1012.20.2) (plain concrete) | Chlorine (Cl) content was reported up to 0.15% (coffee ground), 0.72% (wood) and 0.1% (olive stone). | Reported values are total chlorine not soluble chloride ion<br>Some feedstocks exceed the threshold, but it is uncertain how much is actually soluble<br>Therefore, further investigation required |
| Sulphates (as $SO_3$) | 5.0 wt.% of Portland cement | Reported sulphur contents up to 1.7% (food waste digestate), 0.5% (coffee ground), 0.02% (wood), 0.3% (poultry litter) | Meet the requirements<br>Reported values are sulphur (S) not sulphate ion. It is uncertain how much is actually soluble |
| Other salts (nitrates) | No strongly ionised salts | No reported testing in literature | More investigation required |

Source: AS 2758.1:2014.

The summary assessment against AS 2758.1:2014 criteria does not support that Biochar fine aggregate be considered a direct replacement for conventional fine aggregates, with insufficient information relating to the durability and impurities, and challenges resulting from the very high water absorption and lightweight characteristics. These are discussed further in Section 4.

# 4 Discussion and Conclusion

From a compliance perspective, the feasibility of biochar as a fine aggregate for TMR concrete is currently limited. It falls into the lightweight or ultra lightweight aggregate category but may pose risks of segregation during mixing. The very high water absorption values for the material may also create challenges for workability and mix control. While particle size can be adjusted to meet grading envelopes, possible excessive fines remain a concern. To date, durability properties (sulphate loss, degradation factor and alkali silica reactivity) and impurity limits have not been systematically tested. Although sulphur contents generally meet requirements and alkali silica reactivity risk appears low from its chemical composition, chloride contents up to 0.7% (reported as total chlorine) raise concerns, with no data on soluble chloride. Biochar may also fail organic impurity tests due to its carbon-rich nature. Overall, biochar does not currently comply with MRTS70/AS 2758.1, as a potential fine aggregate source, though it may have potential in non-structural N class concrete applications at very low addition rates consistent with the literature reviewed in this report. Further testing and investigation are required, particularly for longer-term durability behaviour and the effects of impurities in the material on the concrete, before it can be considered viable for TMR use in Queensland.

From a performance perspective, biochar shows potential benefits but remains at an early stage of development. Across the reviewed studies, its incorporation into concrete consistently reduced density and improved thermal and sound insulation. At the low replacement levels that some studies showed (typically between 2% and 15% of fine aggregate replacement by weight, depending on the biochar source), comparable or improved compressive strength and flexural strength were reported. This is mainly attributed to internal curing and matrix refinement effects. Conversely, higher dosages (from approximately 3 to 20% replacement by weight of fine aggregate, depending on the source) generally led to strength reduction due to the increased porosity and weak particle bonding. Workability is expected to drop if introducing biochar below SSD condition. Although some improvements in shrinkage and chloride resistance were reported, the consistent increase in water absorption and void content raises durability concerns. Overall, biochar use in concrete as a fine aggregate replacement may be feasible for non-structural applications, but its suitability for structural use under MRTS70 (both N and S class) remains unproven. There are significant knowledge gaps in its long-term performance and scale-up feasibility.

Based on the data available for this assessment, there is insufficient evidence of sound performance to support acceptance of biochar products as a fine aggregate within concrete specifications. If biochar is to be developed as a fine aggregate in concrete, it is recommended that concrete suppliers conduct further technical work and investigations with proposed mixes to:

- demonstrate acceptable moisture conditioning and control of plastic performance
- demonstrate acceptable hardened concrete properties in accordance with AS 1379, as well as AS 3600 and AS 5100.5, including relationships to creep, drying shrinkage and elastic modulus
- demonstrate the impact on durability performance including chloride migration and carbonation potential, due to the increased porosity of the medium
- demonstrate that the departures in material properties from AS 2758.1:2014 present no risk to the structural performance in concrete.

It is also understood that, currently, there are no real economically viable sources of biochar that could be scaled up in Queensland to provide quantities that would make investing in the required research and development worthwhile. Further, at this time, it appears that any potential benefits related to the carbon negative status of biochar are outweighed by the potential risks and unknowns associated with its use in concrete.

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## Standards and Specifications

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