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Balancing the Mechanical Performance and Environmental Sustainability of Fiber-Reinforced Concrete

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Journal

Journal of Materials in Civil Engineering, 37(7)

ISSN

0899-1561

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Publication Date

2025-07-01

DOI

10.1061/jmcee7.mteng-19454

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1 This document is the author final version of the following article:
2
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4 Schultz Cameron, Cunningham Patrick R., Fan Jin, and Miller Sabbie A. “Balancing the Mechanical
5 Performance and Environmental Sustainability of Fiber-Reinforced Concrete.” *Journal of Materials in*
6 *Civil Engineering* 37, no. 7 (2025): 04025178. <https://doi.org/10.1061/JMCEE7.MTENG-19454>.
7
8

9 For references, please cite the version of record (final version):
10 <https://doi.org/10.1061/JMCEE7.MTENG-19454>
11

Balancing the Mechanical Performance and Environmental Sustainability of Fiber Reinforced Concrete

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Abstract:

Fiber reinforced concrete (FRC) can have improved durability and tensile properties, potentially enabling the more efficient use of concrete and lowering greenhouse gas (GHG) emissions. Yet, systematic quantification of the environmental impacts of FRC, particularly when paired with changes to mechanical properties and the implications for material longevity, are limited. Herein, an assessment following life cycle assessment methodology of four common FRCs was performed, those reinforced with polyvinyl alcohol (PVA), steel (ST), polypropylene (PP), and polyethylene terephthalate (PET). The analysis was bound to a cradle-to-gate scope and solely virgin fiber material production was considered for the environmental impacts. Coupled changes in compressive and tensile strength, environmental impacts, along with the role of material longevity and cost relative to unreinforced concrete were examined. Findings from this work show that, similar to unreinforced concrete, cement remains a key source of GHG emissions in FRC production. However, in FRCs fibers can drive additional emissions by up to 55%. Notably, PVA and ST led to the highest impacts and costs, while minimal for inclusions of PP and PET. Yet ST contributed to the greatest benefits in flexural and compressive strengths. When the effects of longevity were integrated, FRC with PP reinforcement could offer desired emissions reductions with minimal increase in use period and cost, but the other fiber reinforcements considered may need to offer longer service life extension to reduce emissions compared to conventional concrete. These results indicate that FRC can enhance mechanical performance, but fiber type selections should be informed by the design life to achieve actual GHG emissions reductions.

Keywords:

Fiber reinforced concrete; Greenhouse gas emissions; Concrete; Cement; Durability

50 **1. Introduction**

51 Mitigating greenhouse gas (GHG) emissions from industrial production is critical to meeting
52 global climate goals (Davis et al. 2018). Within industrial production, reducing emissions from materials
53 production is key, and it has been noted that decreasing GHG emissions from steel-reinforced concrete
54 is imperative to achieving carbon neutrality by 2050 (Masson-Delmotte 2023). Currently, Portland
55 cement (PC) production exceeds 4 billion metric tons annually (U.S. Geological Survey 2023), and leads
56 to an estimated 7% of anthropogenic CO₂ emissions (International Energy Agency 2018). Material
57 efficiency, in which less raw materials are used to achieve the same function for a given application, can
58 contribute to reducing GHG emissions by avoiding emissions from virgin material production. Such
59 strategies can include reducing the mass of components and/or elongating their use phase (Hertwich et
60 al. 2019). For concrete, these material efficiency strategies (e.g., use of supplementary cementitious
61 materials, low emissions fuels, design-tailored mixture proportioning) and use-life elongation strategies
62 (e.g., durable material use for improved longevity) could reduce GHG emissions up to 21 and 47%,
63 respectively (Miller 2020; Olsson et al. 2023). These reductions are primarily achieved by decreasing
64 the production of PC, the hydraulic binder in concrete, and steel reinforcement. Concrete performs very
65 well in compression; however, it has comparatively weak tensile strengths (Nuruddin et al. 2014). Thus,
66 steel rebar reinforcement is typically added to carry post cracking tensile loads. Notably, steel is also a
67 high-impact material that contributes an additional 7% of anthropogenic CO₂ emissions (Energy Agency
68 2020).

69 One existing alternative to conventional steel reinforced concrete is fiber reinforced concrete
70 (FRC), whose improved durability and tensile properties could extend the useful lifetime of concrete
71 structures. Weak flexural properties in concrete are due to stresses on the tensile surface (Bagherzadeh et
72 al. 2012) making cement-based materials susceptible to cracking from these stresses and limiting their
73 functionality in certain applications (Yang 2011). Furthermore, poor tensile strength, crack resistance,

74 and ductility can lead to durability issues and limit applications (Jang et al. 2014). The use of rebar can
75 introduce additional durability issues in concrete, which may lead to corrosion in the steel and,
76 potentially, to cracking and spalling (Monteiro and Mehta 2006). This failure, in turn, accelerates further
77 corrosion (Fan et al. 2021). Over the last 50 years, fibers have become more common as a means to
78 modify the tensile behavior of concrete (Naaman 2018). Fibers in concrete can improve properties by
79 absorbing energy and slowing crack formation (Bindiganavile et al. 2002; Li et al. 2007). Performance
80 of FRC varies depending on fiber material (e.g., plastic, glass, carbon), size (e.g., fiber length and
81 diameter), shape (e.g., hooked end, twisted, indented), amount of fiber added, fiber-matrix interaction,
82 and loading history (Bandelt and Billington 2018; Shao et al. 2022). Among the improvements noted in
83 the literature, FRC improves flexural strength, impact resistance, tensile strength, ductility, and
84 toughness relative to conventional concrete (Abbass et al. 2018; Wang et al. 2018). If synthetic polymer
85 fibers are used in FRC, they can also be more resistant to corrosion and better suited for aggressive
86 environments (Diab et al. 2020; Shafiq et al. 2016; Vafaei et al. 2022). Fibers for structural applications
87 are widely accessible (Atahan et al. 2013), and incorporating fibers into a concrete mixture can reduce
88 the amount of required steel rebar, thus lowering labor costs (Soutsos et al. 2012) and reducing
89 environmental impacts from steel bars (Katz 2004).

90 Fiber reinforcement can also extend the service life of concrete structures, thus requiring less
91 frequent maintenance and/or offsetting further emissions from replacement. At a structural level, the
92 characteristics of FRC can contribute to increased material efficiency, where lower volumes of material
93 are needed. Fan et al. (2023) and Shao et al. (2023) suggest that the cross-sectional area of ultra-high
94 performance concrete (UHPC), a type of FRC typically containing steel fibers, can be greatly reduced
95 relative to conventional concrete due to significantly higher tensile and compressive strength of UHPC
96 material. Thereby, the total volume of FRC materials can be reduced, lowering the GHG emissions
97 associated with building a new structure. Namely, a reduced cross-section size compared to

98 conventional reinforced concrete can be associated with fewer reinforcing bars while achieving the same
99 load capacity (Shao et al. 2023). As reinforcing bars have been shown to be a notable fraction of
100 reinforced concrete member GHG emissions (Kourehpaz and Miller 2019), fewer reinforcing bars can
101 lead to lower emissions. Moreover, when the total GHG emissions at the system level are considered,
102 more benefits may be achieved through optimization of the design (Shao et al. 2023). Further, any
103 reductions in deadload that could be achieved through these improvements to the material performance
104 can potentially lower the demands of members in the structure, which can be used to reduce cross-
105 sectional areas and lower GHG emissions (Miller et al. 2015). Certain types of FRCs have showed
106 significantly longer service lives and require less frequent maintenance (Fan et al. 2022). As such,
107 impacts for repair, rehabilitation, and replacement could be further reduced over the lifetime of the
108 structure (Deb et al. 2020). This improvement to service life could offer pathways to reduce cement
109 production, for example, by extending the functional service of the concrete, such as through
110 repurposing long-lived buildings (Gursel et al. 2023). If it is possible to leverage longer service lives of
111 materials, additional GHG emissions from new construction could be avoided, which can again
112 contribute to material efficiency (Olsson et al. 2023).

113 While the beneficial material performance effects of integrating fiber reinforcement into concrete
114 mixtures are well studied, their effects on environmental impacts must be further investigated. In
115 addressing such concerns, Sbahieh et al. (2022) evaluated the mechanical performance and
116 environmental impacts of carbon, aramid, basalt, and glass FRC and showed the use of basalt and glass
117 fiber reinforced beams led to a 40 and 43% reduction in CO₂ emissions, respectively, compared to steel
118 reinforced beams. Fořt et al. (2021) compared the performance of basalt and steel (ST) fibers in FRC
119 and found that basalt reinforcement contributed to lower CO₂-eq per unit compressive or flexural
120 strength relative to the use of ST fibers. Sbahieh et al. (2023) compared more materials: concrete beams
121 reinforced with carbon fiber, glass fiber, steel glass fiber, and steel rebar. Their results found that, while

carbon fiber led to the best mechanical performance, glass fiber had the lowest environmental impacts followed by steel glass, steel rebar, and then carbon. Chottemada et al. (2023) found contradicting results when comparing the use of ST, PP, and glass fibers in alkali-activated concrete, finding glass FRC to have the highest GHG emissions followed by ST and PP, which had the lowest cost impact. Yahyaee and Elize (2024) further compared the use of ST and carbon fibers in mixtures with supplementary cementitious materials, finding a mix of 50% ground granulated blast furnace slag (GGBS) and 1.5 fiber volume percent (fv%) ST fibers to have minimal compressive strength reduction while increasing flexural strength, abrasion resistance, and lowering of GHG emissions by 39.3% for a 3.9% cost increase. Additionally, Khelifa et al. (2021) studied the impacts of natural (e.g., jute, bamboo) fibers for use in FRC, comparing Alfa and PP, finding Alfa FRC to have a ‘negative’ carbon footprint (attributed to CO₂ plant uptake) while increasing tensile strength by 4.92% at 112 days. Akbar and Liew (2021) examined the environmental impacts of FRCs with six common fiber reinforcement types: recycled carbon, basalt, glass, polypropylene (PP), polyvinyl alcohol (PVA), and virgin carbon fiber. Their findings suggested recycled carbon fiber performed best across mechanical performance, cost, and environmental impact. Notably, recycled materials are commonly assumed to have limited environmental impacts as they have already performed one service life. These initial works provide insight to the environmental impacts of FRC; however, a systematic approach capturing the variation in FRC mixture proportioning, effects on material performance, and environmental impact quantification is needed to address the cases in which FRC can lead to desired GHG emissions reductions relative to conventional concrete. Additionally, the use of consistent scope, assumptions, and methodology for environmental impact modeling is essential to making fair comparisons amongst FRC mixtures.

In this work, the mechanical properties and environmental impacts of FRC reinforced with steel (ST), polypropylene (PP), polyvinyl alcohol (PVA), or polyethylene terephthalate (PET) fibers are paired to systematically quantify pathways to reducing GHG emissions through use of FRCs. The

146 mechanical performance of Normal (<1.5 fv%) and Ductile (2-4 fv%) FRC are compared. Both the
147 environmental impacts and characteristics of FRC produced with different mixture designs are
148 considered. Using reported material properties, both the mechanical performance and the environmental
149 impacts of FRC mixtures are integrated to facilitate comparisons, focusing on column and beam
150 applications, to recommend mixtures that can reduce environmental impacts. Over 120 mixtures are
151 analyzed using the OpenConcrete tool (Kim et al. 2022), which allows for consistent modeling and
152 comparison amongst a variety of data sources. Finally, the potential effects of service life elongation
153 from FRCs on reducing GHG emissions is examined along with a cost assessment.

154

155 **2. Methods**

156 **2.1 Data Acquisition**

157 To draw comparisons across different FRC mixtures, mixture proportion and material
158 performance data were collected from a range of literature sources (full dataset presented in the
159 Supporting Information). Articles were selected by searching Google Scholar, Clarivate Analytics' Web
160 of Science, The University of California Libraries' Melvyl Catalog, and American Concrete Institute's
161 International Abstracts Portal with relevant terms (e.g., "PVA Fiber Reinforced Concrete",
162 "Polypropylene Reinforced Concrete"). To compare changes based on fiber type and PC content,
163 mixtures with supplementary cementitious materials or more than one fiber type were excluded because
164 these materials affect both performance and environmental impacts. Further, fiber materials were limited
165 to PVA, PP, ST, and PET, which are well studied for their mechanical properties and provided a larger
166 sample size for analysis. The collected data included: mixture proportions, test specimen dimensions,
167 28-day flexural strengths, 28-day compressive strengths, and fiber dimensions. In total, 86 works were
168 reviewed, and 19 articles met the search requirements. These 19 articles provided data for 120 mixtures

169 (13 with PP fibers, 24 with PVA fibers, 50 with ST fibers, 12 with PET fibers, and 21 control mixtures
170 without fibers). The mixtures collected, article sources, and unit conversions performed are shown in the
171 Supporting Information. To address the effects of test specimen size, the equations proposed by Yi et al.
172 (2006) were used to calculate the general strength of each mixture. These strengths, with the effect of
173 dimension removed, were used to analyze the environmental impacts from a mechanical performance
174 perspective.

175

176 **2.2 Environmental impact assessment**

177 ***2.2.1 Goal and scope***

178 To systematically quantify the impacts from producing FRC with PP, PET, PVA, and ST, the
179 primary stages of a life cycle assessment were followed. The scope considered was from raw material
180 acquisition to factory gate, as shown in the cradle-to-gate boundary illustrated in **Fig. 1**. Raw material
181 acquisition, processing, transportation, and batching were modeled for each FRC mixture constituent.
182 The use, maintenance, and end-of-life phases were left outside the scope of this analysis; however, the
183 potential to reduce cradle-to-gate impacts of new materials through increased in-use longevity of FRC
184 was considered. To compare the environmental impacts, a unit of 1 m³ of concrete was used in
185 conjunction with comparison indices that include material performance (described in **Section 2.3**).

186

187 ***2.2.2 Inventories***

188 The environmental impacts for 1 m³ of concrete were quantified using the OpenConcrete tool
189 (Kim et al. 2022), which offers an inventory with consistent modeling methodologies for constituent
190 production, concrete batching, and transportation. OpenConcrete also offers the ability to account for
191 variations in concrete mixture proportions, PC kiln technology, thermal energy resources used in cement
192 kilns, electricity grids used in the production of common concrete constituents (e.g., PC, aggregates,

several chemical additives), and transportation impacts throughout the value chain (Kim et al. 2022). In this work, concrete and its constituents were modeled as being produced in Northern California using the California average kiln efficiency, the US average kiln fuel mix, and California average electricity grid mix. The exception being for the fibers and plasticizers. The plasticizers were modeled with the Texas electricity grid, as it was assumed plasticizers would be imported from a region with high prevalence of chemical production (United States Environmental Protection Agency 2023). The OpenConcrete tool does not contain fiber reinforcement, so to model the impacts of fiber materials, inventories were used for PVA (Jungbluth et al. 2012), PET (European Commission (Joint Research Centre) 2017), PP (European Commission (Joint Research Centre) 2017), and ST (European Commission (Joint Research Centre) 2017). In these cases, only the material production impacts were considered, while additional processing (e.g., fiber extrusion, coating, dyeing) were outside the scope of this work. These model sources and assumptions for each of the constituents considered are reported in **Table 1**. Considering the different masses of fiber specified for each FRC mixture examined, the outputs from each of these inventories were combined with the mixtures modeled in OpenConcrete to quantify the total environmental impact of a FRC mixture.

For all constituents, the OpenConcrete tool was also used to model the transportation of material to the concrete mixing facility using transportation parameters shown in **Table 1**. Petroleum and chemical products, including plasticizer (and superplasticizer) and polymer fiber, were modeled as being transported from the Gulf of Mexico. This input is based on the assumption that synthetic polymer production is co-located with petroleum processing, which is heavily prevalent in the Gulf Coast of the United States (United States Environmental Protection Agency 2023). ST fiber was assumed to be co-located with steel production mills in West Virginia, based on areas with high levels of ferroalloy production in the United States (United States Environmental Protection Agency 2023). These two locations are nearly equidistant to California. Therefore, the transportation of plasticizers, polymer

217 fibers, and steel fibers were modeled as being transported a distance of 3,000 miles (4,828 km) to
218 California by truck. The transportation of the other concrete constituents was also assumed to be by
219 truck, based on distances estimated and relative fraction of transportation mode for concrete constituents
220 in the United States, as reported by Marceau et al. (2007). Water was assumed to be locally available
221 and negligible transportation distance was assumed.

222 The OpenConcrete tool quantifies impacts across 11 categories: GHGs, nitrogen oxides (NO_x),
223 sulfur oxides (SO_x), volatile organic compounds (VOCs), carbon monoxide (CO), particulate matter with
224 diameter less than 10 μm (PM₁₀), particulate matter with diameter less 2.5 μm (PM_{2.5}), lead (Pb), direct
225 energy demand, water consumption, and water withdrawal (Kim et al. 2022). In this work, GHG
226 emissions were the primary focus due to the current urgency in mitigating these impacts from concrete
227 production.

228

229 **2.3. Comparison Indices**

230 Increased material efficiency, via improved material performance and reduced material demand,
231 is a key factor of the potential environmental sustainability of FRCs. As such, this work includes two
232 comparison indices from Miller et al. (2016) that integrate environmental impacts and mechanical
233 performance for an axially loaded column (1) and for a beam in bending (2). These indices address the
234 combination of production-related impacts and material behavior to understand cumulative effects on
235 member environmental impacts. In both cases, a lower value represents a more desirable combination of
236 production-related impacts and material behavior. For the column, X_{axial} represents the comparison index
237 (in units of CO₂-eq/m³ per MPa compressive strength), i is the environmental impact from 1 m³ of
238 concrete (in kg CO₂-eq), and f_c is the compressional strength of the specimen (in MPa).

$$X_{axial} = \frac{i}{f_c} \quad (1)$$

239 $X_{bending}$ represents the comparison index for a beam in bending (in units of CO₂-eq/m³ per MPa^{0.5}), f_t is
240 the flexural strength of the specimen in MPa, and i is the environmental impact, as previously defined.

$$X_{bending} = \frac{i}{f_t^{0.5}} \quad (2)$$

241

242 **2.4 Longevity Modeling**

243 As an estimate of the potential environmental benefits from increased longevity possible through
244 use of FRCs, findings from the environmental impact assessments were paired with concrete longevity
245 models. Namely, distributions for the residency period of concrete in water and waste management
246 systems, streets and highways, non-residential buildings, residential buildings, and other concrete uses in
247 the United States (US) were used, based on Kapur et al. (2008). Building on the model in Miller (2020),
248 the potential for increased in-use residency periods to reduce GHG emissions via reducing cement
249 demand were examined. Reported production of cement in the US from 1900 to 2023 (Hatfield 2024;
250 Kelly and Matos 2014) was utilized. Using these in-use residency distributions and the estimated US
251 cement production, the quantity of cement in-stock at any given time was determined. The percent
252 extension of in-use residency necessary from FRCs to counterbalance higher GHG emissions from
253 producing FRCs was determined based on the average GHG emissions calculated in **Section 2.2.2**.
254 These emissions (in kg/m³ of concrete) were normalized per 1 kg of cement used in each mixture. Using
255 the percent difference between the ratio of emissions per kg of cement for each FRC relative to concrete
256 without fiber reinforcement, the required service-life of FRC to have the same GHG emissions as
257 concrete without fiber reinforcement was determined.

258 This modeling approach has several limitations and is meant as a first order assessment of how
259 improved longevity may play a role in the selection of FRC over conventional concrete. This approach
260 characterizes material savings that could accrue if concrete systems could be used for longer than their
261 current typical residency periods. It does not reflect other aspects that could lead to replacements (e.g.,

aesthetics, required structural changes in capacity). Rather, this assessment reflects the potential benefits from continued use or repurposing, which has been shown to have significant environmental benefits (Gursel et al. 2023). Further, it does not reflect differences in emissions due to technology changes (e.g., improving equipment efficiency, changing fuel resources, or other improvements over the lifespan). Additionally, it does not consider the dynamic effect of emissions, in which it has been shown that a rapid pulse of emissions early on could be worse for cumulative radiative forcing than the same quantity of emissions spread out over a long time-horizon (Kendall 2012). Rather, this is a simplified first-order approach to understanding how improved longevity of concrete could contribute to reduced emissions.

270

271 **3. Results**

272 **3.1 GHG emissions of fiber reinforced concrete**

273 The modeled GHG emissions and prices for each of the concrete constituents and fiber types
274 considered are compared in (**Table 2**). As noted in the literature, for conventional concrete constituents,
275 aggregates and water have significantly lower emissions on a per kg basis than PC (Cunningham et al.
276 2021). PC, while having higher emissions than aggregates and water, had lower GHG emissions on a per
277 kg basis than fibers. The PC modeled had GHG emissions of 0.8 kg CO₂-eq per kg PC while the
278 emissions from fiber production ranged from 2.0 to 11.27 kg CO₂-eq per kg fiber (**Table 2**).

279 The average composition by constituent mass and average GHG emissions is compared in **Fig. 2**.
280 Despite the higher emissions from fiber production on a per kg basis, PC was the primary driver in GHG
281 emissions for the mixtures assessed. For mixtures without fibers, PC was responsible for an average
282 97% of the GHG emissions. When fibers were included, the relative contribution of PC to the mixture
283 GHG emissions decreased because of the inclusion of higher-emitting fibers. For concrete mixtures
284 containing PP, ST, PVA, and PET, the PC contributed an average 94%, 71%, 71%, and 84% of the total

GHG emissions, respectively. In these mixtures, the fibers were the second-highest contributors to GHG emissions. For an average 0.86 fv%, ST fibers contributed 27% of the GHG emissions, which was the highest average fiber contribution of the four fiber types. While the ST fibers were the lowest emissions fibers on a per kg basis, ST has a significantly higher specific gravity ($SG = 7.833$) than the polymeric fibers and, therefore, a larger mass for the same volume. PVA fibers, with the highest GHG emissions on a per kg basis, had an average 1.27 fv% and contributed 25% to the total GHG emissions. PP and PET contributed a smaller fraction to the environmental impact, averaging 3% and 12% respectively. Other constituents such as aggregates and superplasticizers had small contributions to the GHG emissions. The combined impact of these other materials was at most 13% of the GHG emissions for a mixture and transportation was at most 0.02% of the GHG emissions. Thus, the GHG emissions of FRC are largely influenced by the fiber content, fiber type, and cement content.

While fiber and PC contributed the majority of GHG emissions in FRC, the modeled FRC mixtures exhibited a wide range of GHG emissions (**Fig. 3**). Beyond the quantity of each constituent, the contribution of fibers to the GHG emissions for an FRC mixture vary based on the impact associated with the fiber type. PVA reinforced mixtures had the highest impacts, averaging 775 kg CO₂-eq/m³. In one case, over 50% of the GHG emissions were from the PVA fibers for a PVA FRC with 3 fv%. Notably, PVA mixtures also had the greatest variability of the FRC mixtures studied, ranging from 452 kg CO₂-eq/m³ to 1310 kg CO₂-eq/m³. The mixtures containing ST fibers had the second highest emissions, averaging 485 kg CO₂-eq/m³ with a maximum of 714 kg CO₂-eq/m³. The ST fibers contributed up to 44% of the GHG emissions in a mixture. The PP and PET mixtures had lower impacts, averaging 357 kg CO₂-eq/m³ and 363 kg CO₂-eq/m³, respectively. This result is due to the lower density of PP ($SG=0.907$) and PET ($SG=1.335$) fibers combined with their low GHG emissions. The PP and PET mixtures were in a similar range of GHG emissions to those without fibers, which on average had emissions of 363 kg CO₂-eq/m³. These results portray the complex relationship between the GHG

emissions of concrete constituents in FRC mixtures. While fibers have notable impacts, particularly PVA and ST, PC content drives the GHG emissions associated with a mixture. Across all the FRC mixtures evaluated, PC made up an average contribution of 76%, followed by fibers with an average contribution of 21%.

3.2 Comparing GHG emissions and mechanical properties

Comparison indices that integrate mechanical performance were used to identify fiber types and fv% that result in the most beneficial combined effects of cradle-to-gate environmental impacts and mechanical performance. **Fig. 4** shows the axial and bending performance indices of FRC for a column application and a beam in bending application, respectively, relative to fv% and PC content. The mixtures with the best combination of characteristics have the lowest index value as this indicates the lowest environmental impact per unit strength. These indices can also be used to define specified environmental impact and mechanical performance thresholds. For example, a minimum strength requirement can be established or maximum GHG emissions thresholds can be chosen and only mixtures meeting those established thresholds be considered.

In **Fig. 4**, ST fibers are shown to contribute to the lowest associated GHG emissions per unit strength in a column application. For the column, the average X_{axial} (units of kg CO₂-eq/m³/MPa) was 8.4 for ST FRC, approximately 20-40% lower than the other FRCs on average. The average value for PP FRC was 13.4, for PVA FRC was 13.3, and for PET FRC was 10.5. Notably, the concrete mixtures with no fibers led to both the best and the worst combination of GHG emissions and compressive strengths ($X_{\text{axial}} = 5.04$ and 20.7, respectively). These results suggest the benefits gained from fibers may not consistently outweigh the emissions associated with their use. Optimizing the concrete mixture proportioning should be considered the best route to achieving the desired performance characteristics while mitigating GHG emissions.

333 In bending, the PP and PET fibers had the best combination of mechanical strength and GHG
334 emissions, on average. For X_{bending} (units of $\text{kg CO}_2\text{-eq/m}^3/\text{MPa}^{0.5}$), the average was 161.9 for PP FRC,
335 172.4 for ST FRC, 300.3 for PVA FRC, 168.3 for PET FRC. The FRC mixture with the best
336 combination of GHG emissions and flexural strength for this application contained PP fibers. Again, a
337 concrete mixture with no fibers had the best overall combination of GHG emissions and flexural
338 strength (average $X_{\text{bending}} = 107.5$).

339 The comparison indices suggest that the use of PP or PET fibers can allow for potential benefits
340 in bending performance via fiber addition without compromising environmental impact in relation to
341 conventional concrete. However, the performance of these mixtures was nearly indistinguishable from
342 the control sample. The flexural strengths of control, PP FRC, and PET FRC were 5.2, 4.7, and 5.1 MPa
343 respectively. In contrast, the ST FRC and PVA FRC had average flexural strengths of 8.0 and 6.6 MPa,
344 respectively. This increase in performance comes with a tradeoff in environmental impact.

345 In the case of the bending application, there is a weaker relationship between the mechanical
346 properties and the comparison index as there was for the axially loaded column. For the column, there is
347 1:1 relationship between increasing strength and reducing the X_{axial} ; this 1:1 relationship is also present
348 for GHG emissions and reducing the X_{axial} . Thus, the improvement in compressive strengths from ST
349 FRC and PVA FRC above conventional concrete, 67.8 and 63.7 MPa over 45.1 MPa respectively, is
350 more significant. However, for the bending members, the denominator containing flexural strength is to
351 a power of $\frac{1}{2}$, making an increase in flexural strength not as powerful at reducing the X_{bending} as a
352 reduction in GHG emissions. Therefore, a lower environmental impact mixture, such as those without
353 fibers, can have a better index for bending considerations. However, while a very weak member that has
354 low emissions can lead to a low X_{bending} , it may not meet appropriate design thresholds for performance
355 or other desired characteristics (e.g., durability). Depending on the properties desired from FRC,
356 different fibers may be selected based on the desired mechanical performance, environmental impact,

357 and other necessary thresholds for that application. For example, UHPC (compressive strength ranges
358 from 120 MPa to 210 MPa) normally contains ST fibers, while engineered cementitious composites
359 (ECC) (compressive strength ranges from 30 MPa to 90 MPa) normally have PVA fibers (Graybeal
360 2006; Li and Leung 1992). PP and PET fibers could be used for low-strength mixtures where flexural
361 performance is of greatest concern.

362

363 **3.3 Assessing longevity of fiber reinforced concrete**

364 The longevity analysis shows that if FRCs are able to reduce the need for material production
365 through increased in-use longevity, there could be associated reductions in emissions. Because the use of
366 PP and PET fibers in FRCs did not substantially increase the average cradle-to-gate GHG emissions
367 relative to concrete without fiber reinforcement, the increased longevity these materials would need to
368 achieve to counterbalance emissions from material replacement were low. These findings differ for the
369 ST or PVA FRCs, which may need to offer substantial improvements in material efficiency through
370 mechanisms such as improved longevity to counterbalance their higher production emissions.
371 Specifically, using the US material residency periods and the rate of new material production, for PP
372 FRC, a 6.5% increase in material longevity could contribute a ~3% reduction in material production,
373 which would result in emissions equivalent to the average GHG emissions of concrete without fibers.
374 For the PET FRC, a ~16% reduction in material production would result in emissions equivalent to the
375 concrete without fibers, attainable through a 52% increase in material longevity using the US statistics.
376 Based on the longevity modeling efforts, the shift in average annual removals necessary for these
377 concrete mixtures are shown in **Fig. 5**. Notably, even if the ST and PVA concrete mixtures offered
378 higher in-use residency periods, supported by improved material performance, they could not have
379 resulted in lower GHG emissions than concrete without fiber reinforcement. Two factors are driving this
380 result: (1) the rate at which concrete has been removed from use is low; and (2) new concrete has been

381 added to support new infrastructure and building growth (as opposed to solely replacing concrete taken
382 out of use). This analysis suggests the emissions associated with producing ST FRC or PVA FRC would
383 have led to larger GHG emissions than concrete without fiber reinforcement even if these FRCs made it
384 such that all concrete use in the US from 1900 up until today did not need to be replaced and was still
385 serving its function.

386 While adding fibers can increase the material efficiency and service life of a concrete structure,
387 these results do not reflect the large range in GHG emissions of the FRCs. For example, using average
388 emissions for the mixtures analyzed, the relatively brief increase in longevity for PP FRC required to
389 counterbalance production emissions may be easier to achieve for a range of applications. With the
390 higher emissions materials, such as the ST FRC or PVA FRC, the increase in longevity needed to
391 counterbalance production-related emissions suggests that these materials may be best suited for high
392 performance applications. For example, the use of ST FRC or PVA FRC may be most desirable in
393 scenarios where steel rebar is highly susceptible to corrosion and frequent replacement of members is
394 expected, where loading conditions are extreme and resilient materials are needed, or where life safety
395 concerns rely on a material that is more durable. Because this work examines the full breadth of
396 applications of concrete within the US, there are many low-performance uses that are encapsulated, and
397 higher emissions FRCs are likely not an environmentally favorable application of resources in these
398 low-performance applications.

399

400 **3.4 Cost Assessment**

401 Economics play a critical role when selecting amongst alternatives, especially when undertaking
402 large-scale infrastructure projects. Using prices for constituents shown in **Table 2**, **Fig. 6** plots the
403 estimated cost per m³ of the mixtures considered in this analysis, separated by fiber type. PP
404 (\$107.59/m³), PET (\$70.09/m³), and control (\$64.53/m³) mixtures had significantly lower average cost

than ST (\$383.80/m³) and PVA (\$234.58/m³). The higher total cost of ST mixtures is most likely attributed to the greater amount needed to maintain fv%, given their higher SG, which also held true for GHG emissions and agrees with Chottemada et al. (2023). Further, while PP had the highest cost per kg (\$12.33/kg), mixtures containing this fiber maintained relatively low cost due to their low SG and fv%. Also, PET's significantly low cost per kg of material is primarily attributed to it typically being sourced from recycled materials (Al-Taie et al. 2020).

411

4. Discussion

Based on the analysis conducted here encompassing environmental impact (CO₂-eq), mechanical performance (compressive/flexural strength), longevity, and cost parameters, it is suggested that the decision of whether to include fibers in a concrete mixture resides on the desired performance characteristics. While PP and PET mixtures reported low emissions (357.0 and 363.4 kg CO₂-eq/m³, respectively) and low cost (\$107.59/m³ and \$70.09/m³) without need for an extended service life, their average flexural strengths (5.1 MPa and 4.7 MPa) were similar to and their average compressive (28.7 and 35.5 MPa) strengths were lower than fiber-less control mixtures (5.2 and 45.1 MPa, respectively); the former being a fundamental characteristic for incorporating fibers in a concrete mixture. Meanwhile, ST and PVA mixtures increased both flexural (8.0 and 6.6 MPa, respectively) and compressive (67.8 and 63.7 MPa) strengths relative to the control, but require more than twice the service life to counteract their high production related impacts (484.8 and 775.3 kg CO₂-eq/m³), while being at a higher price point (\$383.80/m³ and \$234.58/m³). Overall, these findings suggest fiber selection must be dependent on environmental, economic, and mechanical constraints. For low-strength applications, a low-impact fiber such as PP or PET is recommended while ST and PVA fibers could be used for high/moderate strength applications such as those in UHPC/ECC.

When comparing with the literature, Ghali et al. (2023) found PP, ST, and PVA FRC to have impacts of 373.6, 382.3, and 385.4 kg CO₂-eq/m³ respectively. While the magnitudes vary, which could be attributed to differences in mixture proportioning and/or impact accounting, the trend of PP < ST < PVA held true for GHG emissions, while PP < PVA < ST was consistent with the cost assessment findings. Additionally, Akbar and Liew (2021) found PVA to have higher GHG emissions and cost than PP FRC, in agreeance with these results. Nikbin et al. (2022) found recycled PET and virgin ST mixtures, 5 and 0.5 fv% respectively, to have a GHG release of 375.6 and 584.7 kg CO₂-eq/m³, falling within the bounds of **Fig. 3** and agreeing with the average trend of PET < ST for cost and environmental impacts. These examples highlight the importance of consistent modeling assumptions to make comparisons amongst fiber materials for a variety of mechanically tested mixtures. This study served to fill this research gap through environmental quantification using the OpenConcrete tool to analyze an abundance of FRC mixtures.

5. Conclusions

This work provides a systematic quantification of the mechanical performance and greenhouse gas (GHG) emissions of fiber reinforced concrete (FRC). The analysis compared four common fiber types: polypropylene (PP), polyvinyl alcohol (PVA), steel (ST) and polyethylene terephthalate (PET) and used comparison indices encompassing axial and bending properties to examine drivers for improved strength and reduced GHG emissions for each type of FRC. The assessments of environmental impacts utilized the OpenConcrete tool, following a life cycle assessment (LCA) methodology with a cradle-to-gate scope. Findings show minimizing Portland cement (PC) content remains key to producing lower GHG emissions concrete. However, the lowest emissions FRC mixtures were also dependent on the type and quantity of fiber used. Choosing which fiber material to use depends on the desired

451 performance of the mixture. Additionally, while the inclusion of fibers mostly enhanced mechanical
452 performance, GHG emissions reductions may also require improved application of materials (e.g.,
453 through reduced member size or increased longevity) and higher costs. Important findings include:
454

- 455 • PC remains a large contributor to environmental impact and mechanical performance of an FRC
456 mixture, contributing to 76% of the total GHG emissions on average;
- 457 • Mixtures reinforced with ST fibers had the highest compressive and flexural strengths, and
458 lowest GHG emissions per unit compressive strength of the FRC mixtures;
- 459 • PP and PET fibers had low GHG emissions per unit flexural strength and low cost compared
460 with other FRC mixtures;
- 461 • Control mixtures had the highest and the lowest X_{axial} (and lowest $X_{bending}$) across all mixtures
462 evaluated, suggesting care should be taken when deciding to include fibers in a mixture;
- 463 • For the sum of applications in the United States, the use of ST and PVA FRC would have
464 resulted in larger cradle-to-gate GHG emissions than conventional concrete regardless of a
465 potential increased service life.

466
467 Future work should examine optimal reinforcement design by drawing direct comparisons to
468 reinforced concrete members, expanding the types of fibers examined, considering different fiber
469 lengths and textures and/or addressing the effects of multiple types of fiber in a FRC mixture. Further,
470 considering durability changes across material types, shifts in service life, alterations in structural
471 design, and environmental conditions would enable a more robust comparison amongst this class of
472 materials. Specific applications where FRCs can drive down emissions relative to conventional design
473
474
475
476

477 should also be examined systematically to narrow the appropriate use of these materials to where they
478 would result in the greatest benefit.

479

480 **Acknowledgements**

481 The authors acknowledge funding provided by NSF CBET 2143981. This article represents the views of
482 the authors, not necessarily those of the funder.

483 **Data Availability Statement**

484 Some or all data, models, or code that support the findings of this study are available from the
485 corresponding author upon reasonable request.

486 **Contributions**

487 **C.S.:** Methodology, Investigation, Writing-Original Draft, Visualization. **P.R.C.:** Conceptualization,
488 Methodology, Investigation, Data Curation, Writing-Original Draft. **J.F.:** Methodology, Writing-
489 Original Draft, Review, & Editing. **S.A.M.:** Conceptualization, Methodology, Investigation, Resources,
490 Writing-Original Draft, Supervision.

491 **Declaration of interests**

492 The authors declare no competing interests.

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625 **Table 1.** Model parameters for energy grid mix, transportation distances, transportation mode, process
626 efficiencies, and sources for these inputs.

Material	Environmental impact model	Transport distance, truck (km)	Rational / source
Cement	OC ^a	150	Marceau et al. (2007)
Fine Aggregate	OC ^a	50	Marceau et al. (2007)
Coarse Aggregate	OC ^a	50	Marceau et al. (2007)
Superplasticizer	OC ^a	4828	Distance from Gulf of Mexico to California
Water	OC ^a	0	Assumed, co-located with batching site
PP Fiber	ELCD ^b	4828	Distance from Gulf of Mexico to California
PVA Fiber	Jungbluth et al. (2012)	4828	Distance from Gulf of Mexico to California
PET Fiber	ELCD ^b	4828	Distance from Gulf of Mexico to California
Steel Fiber	ELCD ^b	4828	Distance from West Virginia to California

^a OC = OpenConcrete tool by Kim et al. (2022); ^b ELCD = LCA tool by European Commission (Joint Research Centre) (2017)

627

628 **Table 2.** GHG emissions and prices associated with the production of each concrete constituent from
629 accumulated inventories.

Material	GHG Emissions (kg CO ₂ -eq/kg constituent)	Price (\$USD/kg constituent)
Cement	0.85	9.35×10^{-2} ^a
Fine Aggregate	1.74×10^{-3}	1.40×10^{-2} ^a
Coarse Aggregate	2.66×10^{-3}	8.60×10^{-3} ^a
Superplasticizer	2.47	3.45 ^a
Water	0	0 ^a
PP Fiber	2.23	12.33 ^b
PVA Fiber	11.27	8 ^b
PET Fiber	4.41	1 ^c
ST Fiber	2.00	4.76 ^a

^a Fan et al. (2024); ^b Ghali et al. (2023); ^c Al-Taie et al. (2020)

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648	represent minimum and maximum ranges.	33
649		

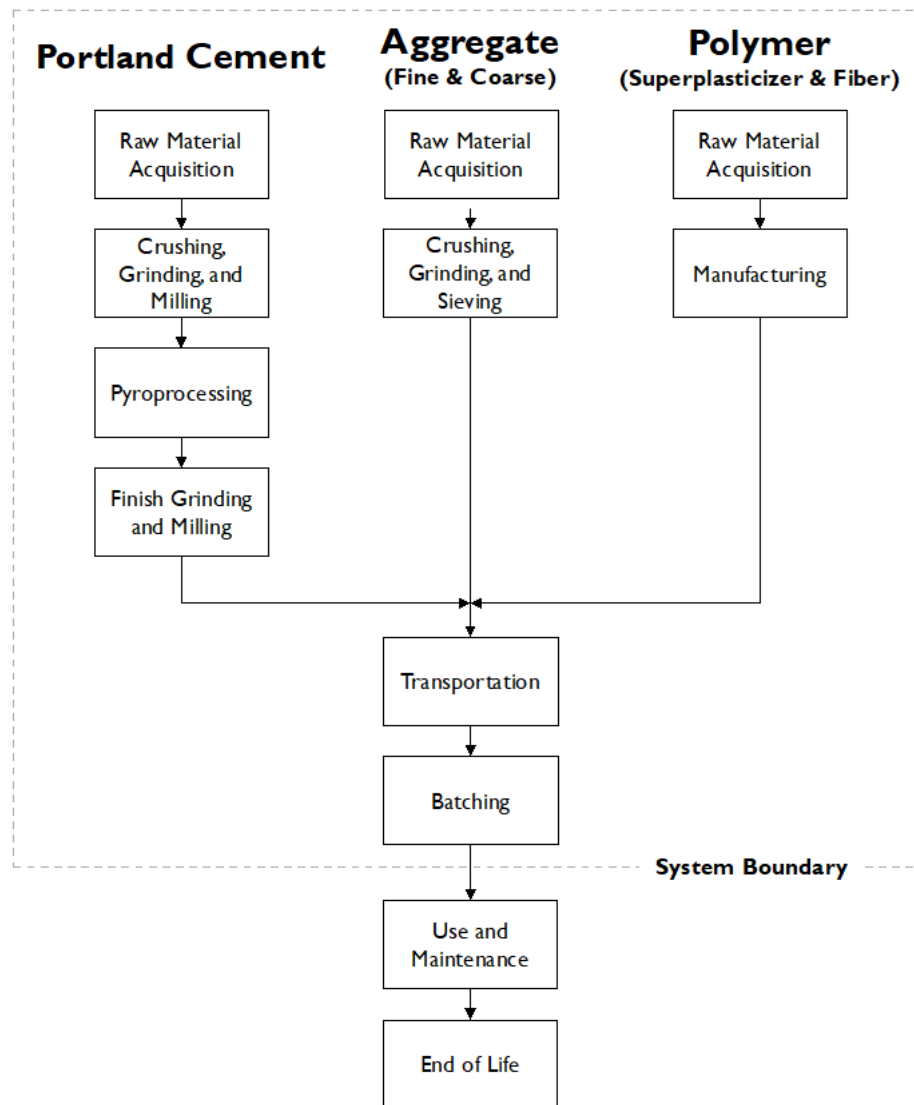


Fig. 1. Process flow diagram encompassing the scope of assessment (grey dashed line illustrates system boundary). While use and maintenance are outside the scope of this primary assessment, changes in material longevity that could mitigate new material production within the system boundary is considered.

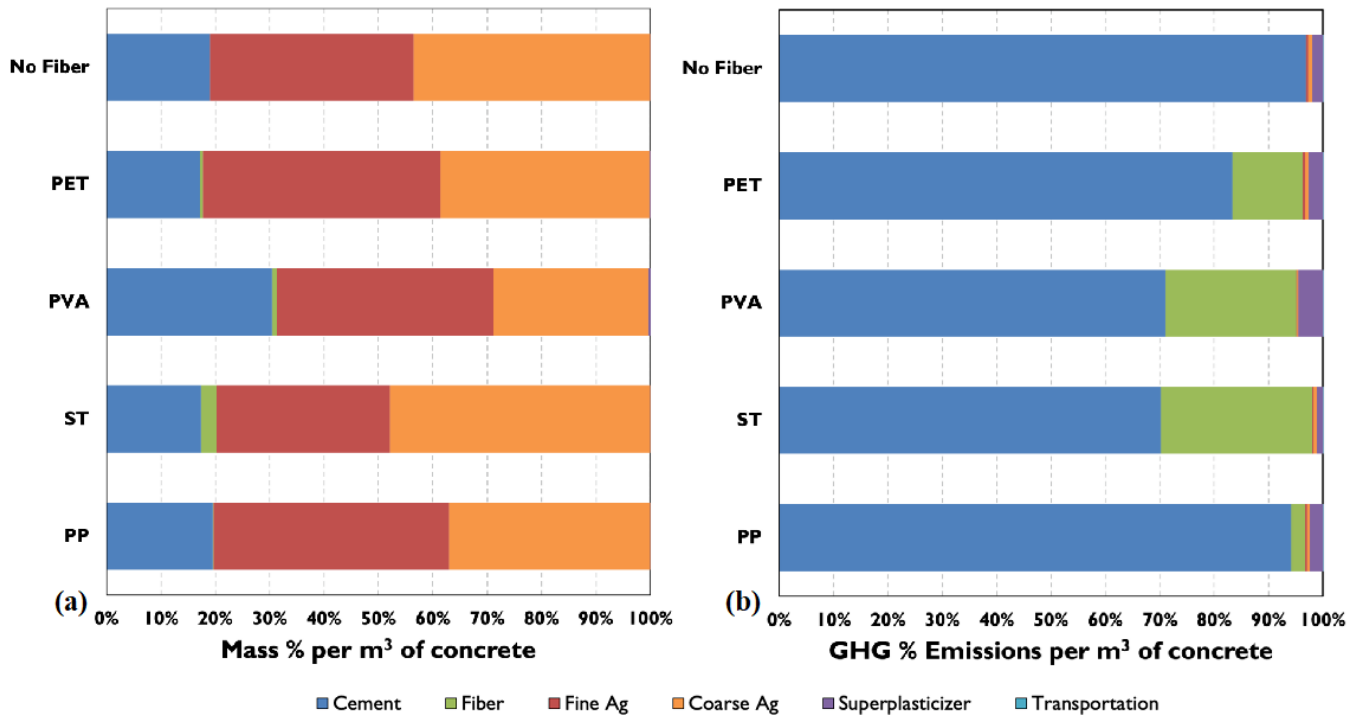


Fig. 2. An overview of the contribution of different concrete mixtures to (a) the average mass proportions of concrete mixtures by fiber type and (b) average contribution of concrete constituent to GHG emissions by fiber type.

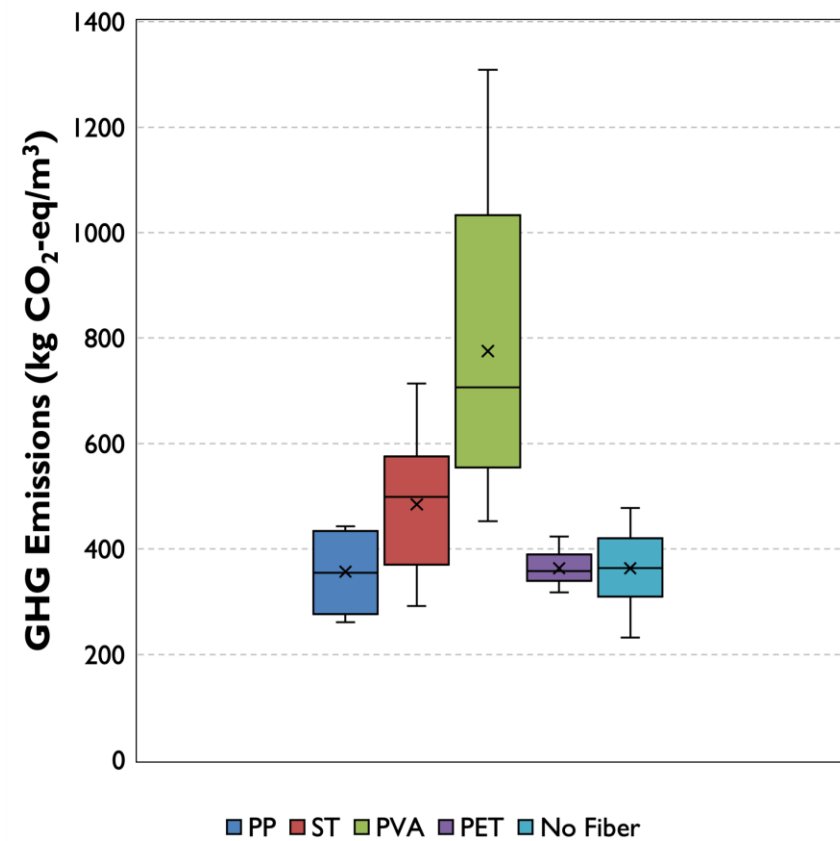


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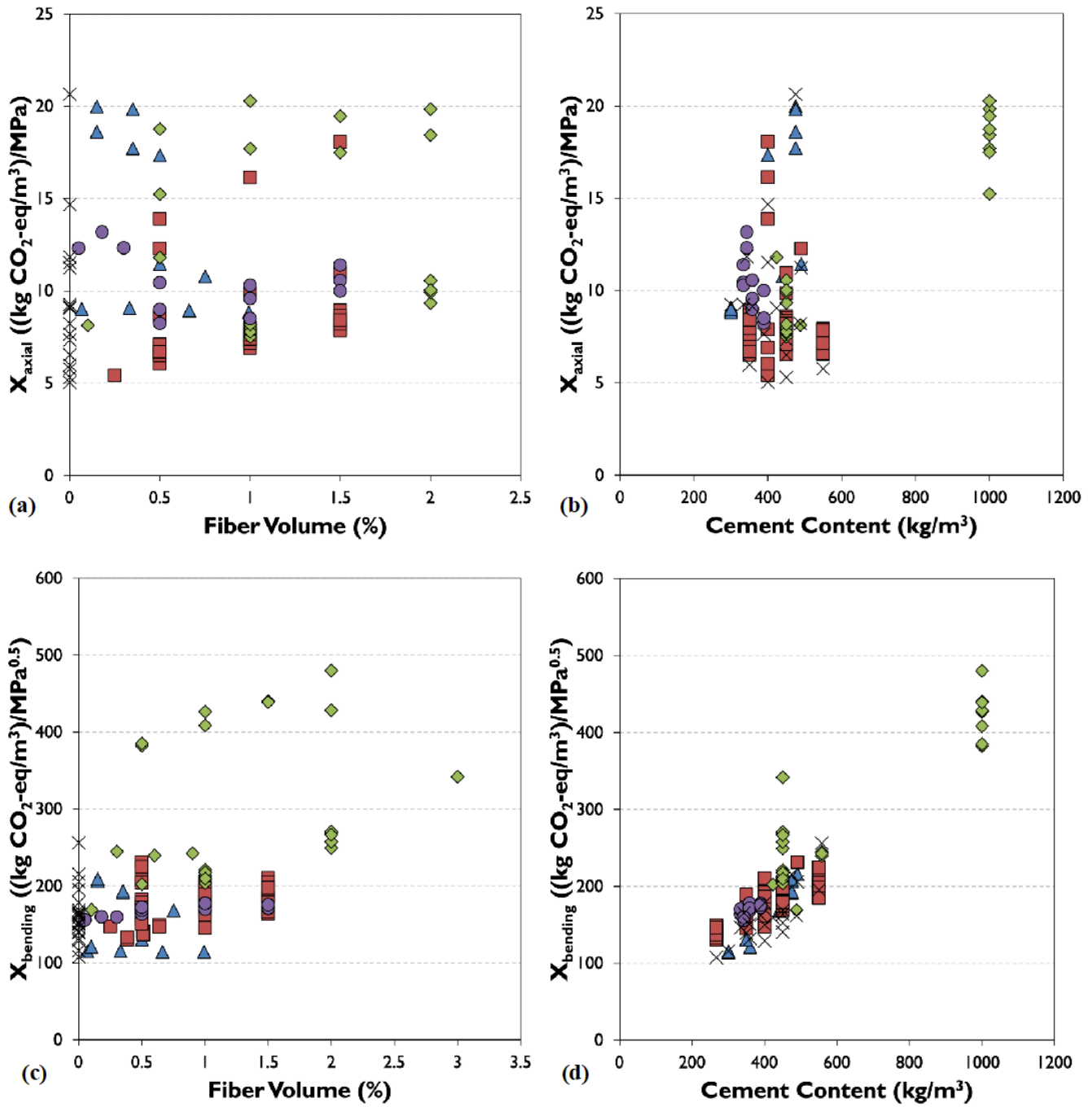


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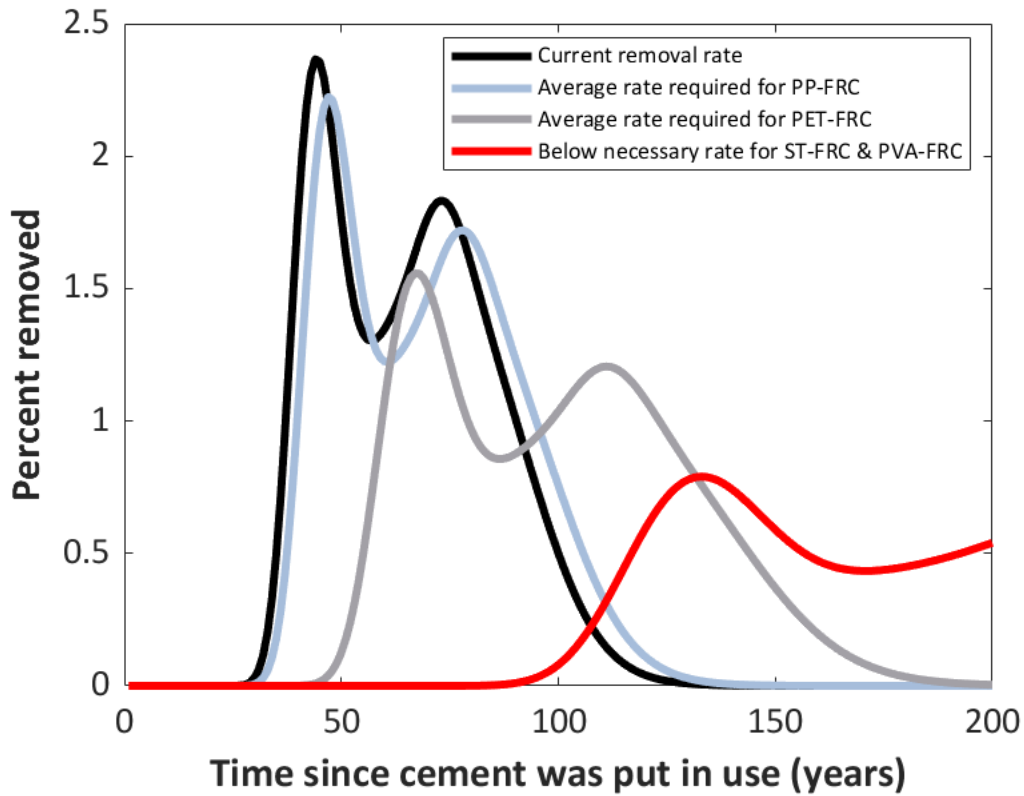


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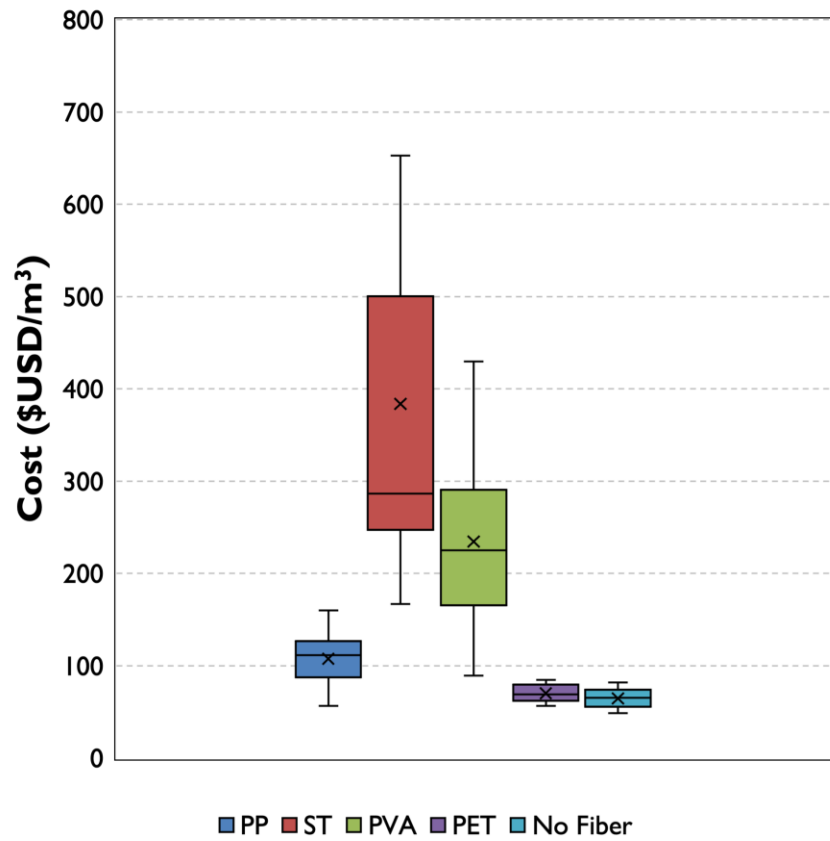


Fig. 6. Box and whisker plot of cost (in USD) per cubic meter associated with concrete mixtures, by fiber type. Mean is marked by “X”, median bar separates upper and lower quartiles, and bars represent minimum and maximum ranges.