

Valorising Gas-Processing Sulfur in Concrete Production: A Techno-Economic and Probabilistic Life-Cycle Assessment of Sulfur Concrete in Uzbekistan

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Abstract

Concrete production in Uzbekistan relies almost entirely on Portland cement, whose cost and carbon intensity are rising, while the country's gas-processing plants generate a large surplus of elemental sulfur that is sold at very low prices or exported over long distances. This study evaluates whether this by-product can be turned into an economically competitive construction material by replacing Portland cement concrete with modified sulfur concrete in precast elements for aggressive environments. A techno-economic model was developed for 1 m³ of concrete of comparable strength (class B40 Portland cement concrete versus modified sulfur concrete), covering materials, process energy, moulds, CO₂ emissions and a 50-year life-cycle cost including replacements. Input prices reflect 2026 conditions in Uzbekistan, and uncertainty in 18 parameters was propagated by Monte Carlo simulation with 10,000 runs, complemented by one-at-a-time sensitivity and break-even analysis. In the base case the initial cost of sulfur concrete (516.6 thousand UZS/m³) is 1.6% lower than that of Portland cement concrete (525.0 thousand UZS/m³), and its CO₂ emissions are 85% lower (60.6 versus 413.6 kg/m³). Under uncertainty, sulfur concrete is cheaper at the production stage in only 21% of runs, because the cost of the polymeric modifier dominates its binder cost, but it has a lower life-cycle cost in 87.6% of runs, with a mean saving of 133.8 thousand UZS/m³ (10.1%). Break-even occurs at a modifier price of about 20.8 thousand UZS/kg or a sulfur price of about 325 UZS/kg. Channelling 100 thousand tonnes of sulfur per year into concrete would displace about 131 thousand tonnes of cement and avoid about 103 thousand tonnes of CO₂ annually. Sulfur concrete is therefore a promising niche technology whose competitiveness depends mainly on low-cost modifiers and on pricing of carbon emissions.

Keywords: Sulfur concrete; concrete production economics; by-product valorisation; life-cycle cost; Monte Carlo simulation; Uzbekistan.

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1. Introduction

Concrete is the most widely used manufactured material, and Portland cement, its binder, accounts for the largest share of both its production cost and its carbon footprint

(Habert et al., 2020; Scrivener et al., 2018). Uzbekistan is no exception: large enterprises produced 12.1 million tonnes of cement in January–July 2026, up from 9.1 million tonnes in the same period of 2024 (UzDaily.uz, 2026), and the exchange price of cement has fluctuated

considerably (Yuz.uz, 2026). At the same time, the country has created a regulatory basis for pricing greenhouse gas emissions: a law establishing a market-based trading system for carbon units took effect on 1 January 2026 (Enerdata, 2026). For concrete producers, this combination of volatile cement prices and emerging carbon costs creates a strong incentive to seek alternative binders.

One such alternative is produced in large quantities by the country's own gas industry. Uzbekistan processes sour natural gas at the Mubarek, Shurtan and Kandym plants and produces about 550 thousand tonnes of elemental sulfur per year, of which around 300 thousand tonnes are exported (BCInsight, 2025). The Mubarek gas processing plant alone has a capacity of 417 thousand tonnes of technical gas sulfur per year (AzerNews, 2017). The domestic market cannot absorb these volumes: reported exchange sales of more than 500 thousand tonnes of sulfur products for just over 9 million US dollars (UzDaily.uz, 2025) imply an average realisation price of less than 20 US dollars per tonne. For a landlocked country, exporting a low-value bulk product over long rail distances yields little value, whereas stockpiling creates environmental risks (Kutney, 2013). Sulfur concrete offers a way to convert this surplus into a construction material. In sulfur concrete, molten sulfur replaces cement and water as the binder: hot aggregates and filler are mixed with sulfur above its melting point (about 119 °C), and the material hardens on cooling, gaining most of its strength within hours rather than weeks (Loov et al., 1974; Mohamed & El-Gamal, 2010). Chemical modifiers such as dicyclopentadiene are added to stabilise the sulfur and improve durability (ACI Committee 548, 1993). Sulfur concrete is highly resistant to acids and salts (Vlahović et al., 2011), which makes it attractive for sewer elements, industrial floors, tanks and drainage structures, where Portland cement concrete deteriorates quickly. Its limitations are equally well documented: it softens at elevated temperatures and burns, so it is unsuitable for applications requiring fire resistance, and its properties depend strongly on the modifier and filler used (Mohamed & El-Gamal, 2009, 2010).

Although the technical properties of sulfur concrete are well studied, its economic assessment remains limited and is usually based on deterministic cost comparisons in countries with different price structures (Dugarte et al., 2019; Mohamed & El-Gamal, 2010). Three gaps are evident. First, the cost of the modifier, which can dominate the binder cost, is rarely treated explicitly. Second, the durability advantage of sulfur concrete in aggressive environments is seldom translated into life-cycle costs (ISO, 2017; Val & Stewart, 2003). Third, no assessment exists for Central Asian conditions, where sulfur is abundant and cheap but cement is also relatively inexpensive. The research question of this study is therefore: under what economic conditions can modified sulfur concrete produced from gas-processing sulfur compete with Portland cement concrete in Uzbekistan? The aim is to quantify its production cost, life-cycle cost and CO₂ emissions under uncertainty, to identify break-even conditions and to estimate the national-scale effect of redirecting part of the sulfur surplus into concrete production.

2. Methods

Functional unit and alternatives

The functional unit is 1 m³ of concrete in precast elements exposed to an aggressive (acidic or saline) environment, such as sewer and drainage elements or industrial floors. Two alternatives of comparable compressive strength were compared (Table 1). The reference is Portland cement concrete (PCC) of class B40, steam-cured, designed by the Bolomey–Skramtaev method with a polycarboxylate superplasticizer so that cement content does not exceed 450 kg/m³ (Bazhenov, 2011; Neville, 2011). The alternative is modified sulfur concrete (MSC) with 342 kg/m³ of sulfur (about 14% by mass), a modifier dosed at 3% of sulfur mass, ground limestone filler and conventional aggregates, in proportions typical of the literature (ACI Committee 548, 1993; Mohamed & El-Gamal, 2010). Both mixtures reach mean compressive strengths of about 50 MPa; the strength of MSC was taken from the literature rather than tested.

Table 1
Mix designs of the compared alternatives (per 1 m³)

Component	PCC B40 (steam-cured)	Modified sulfur concrete
Portland cement CEM I 42.5, kg	449.5	—
Water, L	178.2	—

Component	PCC B40 (steam-cured)	Modified sulfur concrete
Superplasticizer, kg	1.8	—
Sulfur, kg	—	342.0
Modifier (3% of sulfur), kg	—	10.3
Limestone filler, kg	—	200.0
Sand, kg	664.7	740.0
Coarse aggregate, kg	1,092.8	1,100.0
Process heat (steam curing / heating), MJ	250	250
Mean compressive strength, MPa	≈ 51	≈ 50

Note. PCC designed by the author; MSC proportions based on ACI Committee 548 (1993) and Mohamed and El-Gamal (2010).

Cost model

The initial cost of 1 m³ comprises materials, process energy and the amortised cost of moulds:

$$C_0 = \sum m_i \cdot p_i + (E / (\eta \cdot \text{LHV})) \cdot p_g + M, \quad (1)$$

where m_i and p_i are the quantity and price of component i ; E is the useful process heat (steam curing for PCC, heating of aggregates and sulfur for MSC); $\eta = 0.70$ is the burner efficiency; $\text{LHV} = 34 \text{ MJ/m}^3$ is the lower heating value of natural gas; p_g is the gas price; and M is the mould cost per m³. Because MSC can be demoulded after cooling rather than after a day of curing, mould turnover is higher and M is lower (Mohamed & El-Gamal, 2010). The life-cycle cost over $H = 50$ years with replacement of elements at the end of their service life T is

$$\text{LCC} = (C_0 + I + p_{\text{CO}_2} \cdot e) \cdot [1 + \sum_{k=T < H} (1 + r)^{-kT}], \quad (2)$$

where I is the installation cost, e the CO₂ emissions per m³, p_{CO_2} the carbon price and r the real discount rate (ISO, 2017). Emissions were calculated as

$$e = \sum m_i \cdot f_i + (E / \eta) \cdot f_g, \quad (3)$$

with emission factors f_i of 0.80–0.90 kg CO₂/kg for cement, 1.5 for the superplasticizer, 2.0 for the modifier, 0.02 for the filler, 0.005 for aggregates and 0.056 kg CO₂/MJ for natural gas. As a by-product of gas desulfurisation, sulfur was assigned 0–0.10 kg CO₂/kg for handling and granulation.

Input data and uncertainty

Prices reflect conditions in Uzbekistan in 2026 (Table 2). The cement price range follows exchange quotations (Yuz.uz, 2026); the gas price of 2,000 UZS/m³ is the tariff for legal entities in force since 1 June 2026 (Gazeta.uz, 2026); and the sulfur price range spans the implied average exchange price of about 216 UZS/kg (UzDaily.uz, 2025) to delivered prices of up to 600 UZS/kg. The remaining ranges, including the modifier price and dosage, service lives and installation cost, are expert estimates by the author. Each parameter was described by a triangular distribution, and uncertainty was propagated by Monte Carlo simulation with 10,000 runs and a fixed random seed (Law, 2015; Metropolis & Ulam, 1949).

Table 2

Input parameters (triangular distributions: minimum / mode / maximum)

Parameter	Min	Mode	Max
Cement price, UZS/kg	565	650	750
Sand / coarse aggregate price, UZS/kg	60 / 80	70 / 90	90 / 110
Superplasticizer price, thousand UZS/kg	20	25	32
Sulfur price, UZS/kg	216	300	600

Parameter	Min	Mode	Max
Modifier price, thousand UZS/kg	15	20	30
Modifier dosage, % of sulfur	2	3	5
Limestone filler price, UZS/kg	100	150	250
Natural gas price, UZS/m ³	2,000	2,000	2,600
Useful process heat, MJ/m ³	200	250	350
Mould cost: PCC / MSC, thousand UZS/m ³	15 / 5	20 / 7	30 / 10
Installation cost, thousand UZS/m ³	300	500	800
Service life in aggressive environment: PCC / MSC, years	15 / 30	20 / 40	30 / 50
Real discount rate, %	5	8	12
Cement emission factor, kg CO ₂ /kg	0.80	0.85	0.90
Sulfur emission factor, kg CO ₂ /kg	0	0.02	0.10

Note. Sources: Yuz.uz (2026); Gazeta.uz (2026); UzDaily.uz (2025); other values are the author's estimates.

Sensitivity, break-even and scenario analysis

One-at-a-time sensitivity analysis varied each parameter between its minimum and maximum with the others at their modes. Break-even prices of the modifier and of sulfur were obtained by equating the initial costs of the two alternatives. The effect of carbon pricing was evaluated for prices of 0–600 thousand UZS per tonne of CO₂ (about 0–50 US dollars). Finally, a national scenario estimated the effect of channelling 100 thousand tonnes of sulfur per year - about one-fifth of national output - into sulfur concrete. All calculations were performed in Python; the code is available from the author on request.

Production cost and emissions

In the base case the initial cost of MSC is 516.6 thousand UZS/m³, 8.4 thousand UZS (1.6%) lower than that of PCC (525.0 thousand UZS/m³), as shown in Table 3 and Figure 1. The cost structures differ fundamentally: cement accounts for 60.4% of the material cost of PCC, whereas in MSC the largest item is not sulfur (102.6 thousand UZS) but the modifier (205.2 thousand UZS, or 42.0% of material cost). Lower mould costs partly offset the higher material cost of MSC. The CO₂ emissions of MSC are 85.3% lower than those of PCC (60.6 versus 413.6 kg/m³), and MSC requires no mixing or curing water.

3. Results

Table 3
Initial cost and CO₂ emissions per 1 m³ (base case)

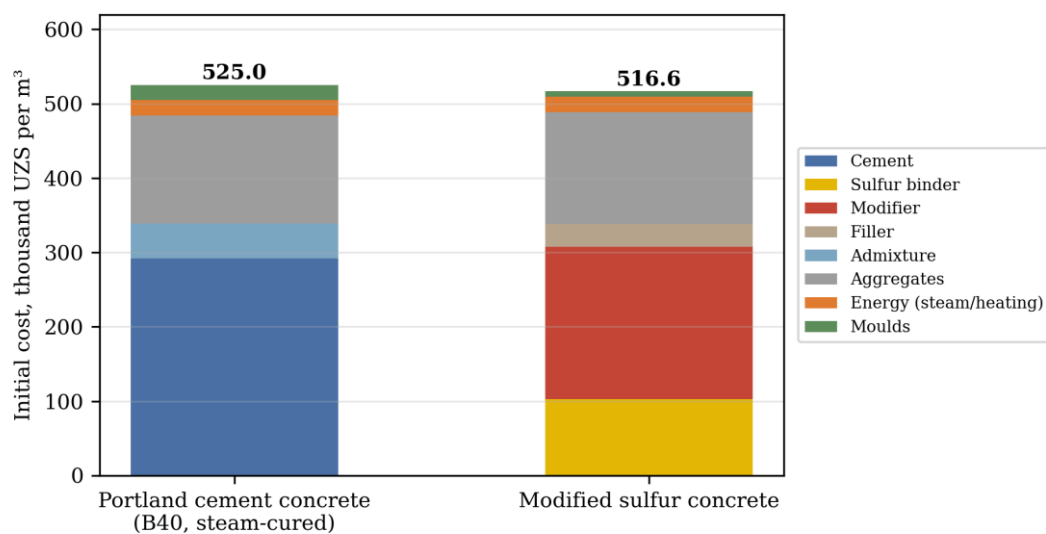
Indicator	PCC B40	MSC	Difference
Materials, thousand UZS	484.0	488.6	+4.6
Process energy, thousand UZS	21.0	21.0	0.0
Moulds, thousand UZS	20.0	7.0	−13.0
Initial cost C ₀ , thousand UZS	525.0	516.6	−8.4 (−1.6%)
CO ₂ emissions, kg	413.6	60.6	−353.0 (−85.3%)

Indicator	PCC B40	MSC	Difference
Mixing water, L	178.2	0	-178.2
50-year LCC, thousand UZS	1,292.1	1,063.4	-228.7 (-17.7%)

Note. Calculated by the author.

Figure 1

Structure of the initial cost of Portland cement concrete and modified sulfur concrete (base case), thousand UZS per m³



Results under uncertainty

The Monte Carlo results (Table 4) reveal an important asymmetry. At the production stage MSC is cheaper in only 21.0% of runs, and its mean initial cost (596.6 thousand UZS/m³) exceeds that of PCC (539.8 thousand UZS/m³), because the right-skewed distributions of sulfur price and modifier price and dosage can raise its

cost considerably. Over the life cycle, however, the longer service life of MSC in aggressive environments reverses the ranking: MSC has the lower life-cycle cost in 87.6% of runs, with a mean saving of 133.8 thousand UZS/m³ (10.1%) (Figure 2). The life-cycle cost of MSC is also less dispersed (standard deviation 132.4 versus 169.3 thousand UZS/m³).

Table 4

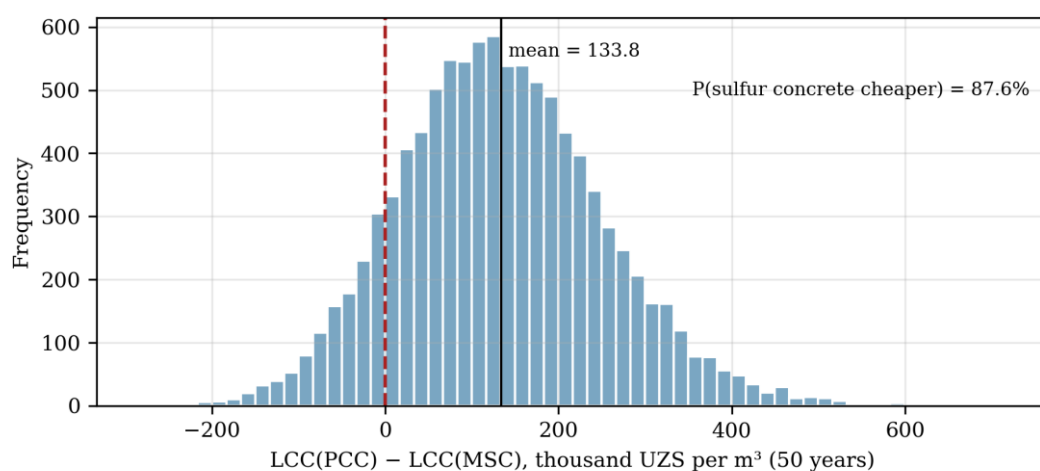
Monte Carlo results (10,000 runs, per 1 m³)

Indicator	PCC B40	MSC
Mean initial cost, thousand UZS	539.8	596.6
Probability that MSC is cheaper initially	—	21.0%
C ₀ (PCC) – C ₀ (MSC): 10th / 90th percentile, thousand UZS	—	-148.5 / +28.2
Mean 50-year LCC, thousand UZS	1,321.6	1,187.8
Standard deviation of LCC, thousand UZS	169.3	132.4
Probability that MSC has lower LCC	—	87.6%

Indicator	PCC B40	MSC
LCC(PCC) – LCC(MSC): mean (10th / 90th percentile), thousand UZS	—	133.8 (–12.6 / +286.8)
Mean CO ₂ emissions, kg	414.9	71.0

Note. Calculated by the author.

Figure 2
Distribution of the life-cycle cost difference between Portland cement concrete and modified sulfur concrete (positive values favour sulfur concrete)



Sensitivity and break-even conditions

The sensitivity analysis (Figure 3) identifies the modifier as the decisive factor. Raising the modifier dosage from 3% to 5% of sulfur mass turns the initial cost advantage of MSC into a disadvantage of 128.4 thousand UZS/m³, while lowering it to 2% increases the advantage to 76.8 thousand UZS/m³. The modifier price and the sulfur price follow in importance, with the cement price acting

in the opposite direction. The break-even modifier price is about 20.8 thousand UZS/kg and the break-even sulfur price about 325 UZS/kg (about 27 US dollars per tonne); the combined break-even line is shown in Figure 4. At the implied exchange price of sulfur, MSC is cheaper at the production stage whenever the modifier costs less than about 23.6 thousand UZS/kg.

Figure 3
Sensitivity of the initial cost advantage of modified sulfur concrete to input parameters

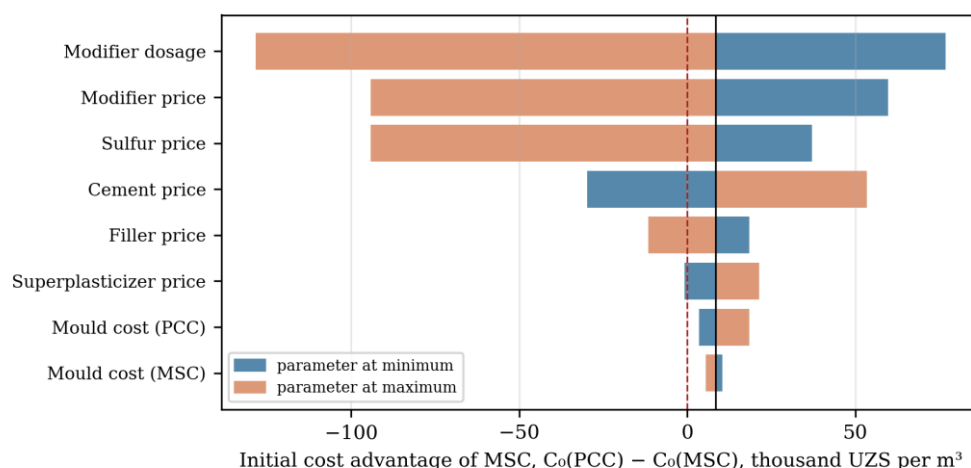
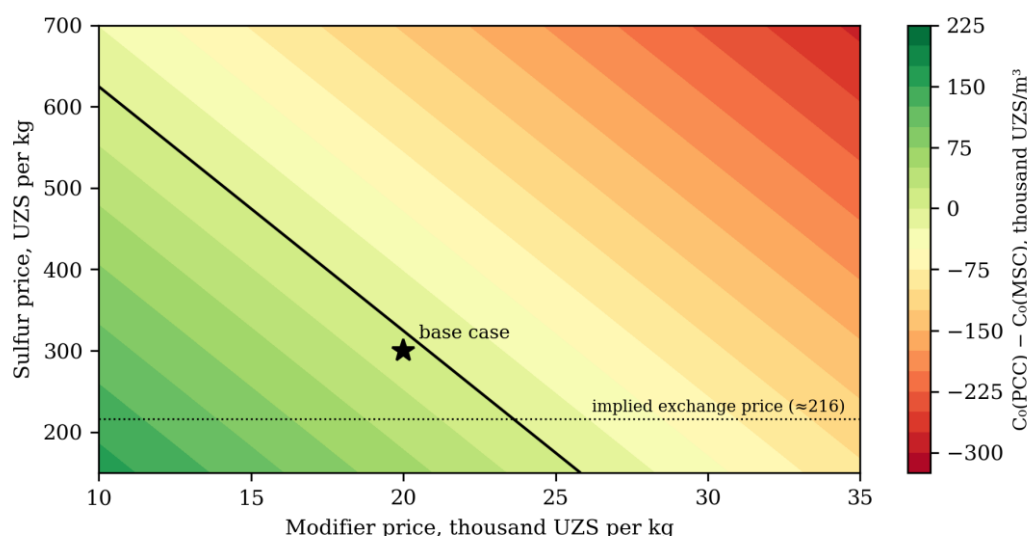


Figure 4

Break-even map of the initial cost advantage of modified sulfur concrete as a function of modifier and sulfur prices (black line - parity)



Carbon pricing and national scenario

Carbon pricing strengthens the case for MSC. In the base case the life-cycle cost advantage of MSC grows from 228.7 thousand UZS/m³ without a carbon price to 297.4, 366.1 and 503.5 thousand UZS/m³ at carbon prices of 150, 300 and 600 thousand UZS per tonne of CO₂. At the

national level, channelling 100 thousand tonnes of sulfur per year into concrete would yield about 292 thousand m³ of MSC, displace about 131 thousand tonnes of cement and avoid about 103 thousand tonnes of CO₂ and 52 thousand m³ of mixing water annually (Table 5).

Table 5

National scenario: 100 thousand tonnes of sulfur per year used in concrete

Indicator	Value
Volume of sulfur concrete, thousand m ³ /year	292
Cement displaced, thousand t/year	131
CO ₂ avoided, thousand t/year	103
Mixing water saved, thousand m ³ /year	52
Value of avoided CO ₂ at 300 thousand UZS/t, billion UZS/year	31.0
Present value of life-cycle savings per annual output (base case), billion UZS	66.9

Note. Calculated by the author.

4. Discussion

The results show that the economics of sulfur concrete in Uzbekistan are shaped less by the price of sulfur, which is already very low, than by the price and dosage of the modifier. This finding refines earlier assessments that emphasised the availability of cheap sulfur as the main

economic argument (Dugarte et al., 2019; Mohamed & El-Gamal, 2010): where cement is also relatively inexpensive, as in Uzbekistan, a costly modifier can eliminate the raw-material advantage. The practical implication is that the development of low-cost modifiers for example, based on by-products of local petrochemical plants is the most effective lever for improving competitiveness. Because gas-processing

plants are located far from the main construction markets, the organisation of sulfur logistics including the discounted rail tariffs already applied to sulfur shipments (UzDaily.uz, 2025) is a further factor that determines the delivered cost of the binder.

The contrast between the production-stage and life-cycle results has important managerial consequences. If procurement decisions are based on the initial price per cubic metre, sulfur concrete will usually lose; if they are based on life-cycle costs in aggressive environments, it will usually win. This mirrors the broader argument for life-cycle costing in construction procurement (ISO, 2017; Val & Stewart, 2003) and suggests that public clients responsible for sewer, drainage and industrial infrastructure should adopt life-cycle criteria when specifying such elements. The emerging carbon market adds a further argument: at a carbon price of 300 thousand UZS per tonne, the value of avoided emissions alone (about 106 thousand UZS/m³) exceeds the mean production-stage cost disadvantage of sulfur concrete in the simulation (56.8 thousand UZS/m³).

For the gas-processing industry, sulfur concrete offers a way to add value to a by-product that is currently sold at less than 20 US dollars per tonne or exported over long distances. Even a modest domestic market of 100 thousand tonnes per year would absorb about one-fifth of national output. Realising this potential requires not only technology but also organisational measures: standards and design codes for sulfur concrete products, pilot production lines near gas-processing plants to minimise transport costs, and cooperation between gas processors, precast producers and infrastructure owners.

The study has limitations. The properties and service life of sulfur concrete were taken from the literature rather than from tests on Uzbek sulfur and aggregates; service lives in aggressive environments are expert estimates; the energy demand of both processes was assumed to be similar; and the fire and thermal limitations of sulfur concrete restrict its use to non-structural or protected applications, which limits the market. Environmental aspects beyond CO₂, such as potential emissions during production, were not quantified. Laboratory testing, pilot production and a full life-cycle assessment are needed to confirm the findings.

5. Conclusion

This study assessed the economic feasibility of producing modified sulfur concrete from gas-processing sulfur in Uzbekistan as an alternative to Portland cement concrete in precast elements for aggressive

environments. In the base case, sulfur concrete is slightly cheaper to produce (−1.6%) and emits 85% less CO₂. Under uncertainty, however, it is cheaper at the production stage in only one run in five, because the modifier accounts for 42% of its material cost; over a 50-year life cycle it is cheaper in 87.6% of runs, with a mean saving of 10.1%. Competitiveness depends mainly on keeping the modifier price below about 20.8 thousand UZS/kg and on adopting life-cycle and carbon-cost criteria in procurement. Redirecting 100 thousand tonnes of sulfur per year into concrete would displace about 131 thousand tonnes of cement and avoid about 103 thousand tonnes of CO₂ annually. Sulfur concrete is therefore a promising niche technology for Uzbekistan, whose development should prioritise low-cost modifiers, standards for sulfur concrete products and pilot production near gas-processing plants.

Declarations

Conflict of interest. The author declares no conflict of interest.

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Ethics approval. Not applicable; the study did not involve human participants or animals.

Data availability. The model inputs are reported in the article; the simulation code is available from the author on reasonable request.

Author contributions. N. U. Dadabaeva is the sole author and was responsible for conceptualisation, methodology, modelling, analysis and writing.

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