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## Review Article

# Performance analysis of lime and GGBS based mortar: A critical review

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### ABSTRACT

Mortar being essential binder in construction, it has a profound effect on performance of structure. This review present, Lime mortars is the significant performer in terms of the strength, durability, and long-term performance with environmental benefits. They also have improved compatibility with masonry units, better flexibility to resist structural movements, and better moisture and vapour permeability, improving resistance to dampness. However, the addition of minimum 2% of ground granulated blast furnace slag (GGBS) along with the Lime as proven to increase the compressive strength in 91 days. While higher levels of substitution led to large compressive strength improvements over the long term. Lime-GGBS mortars reached compressive strengths meeting all mortar designations in 28 to 56 days. A reviewed literature also showed that, durability studies revealed improved resistance to water absorption, abrasion, and chemical attack compared to conventional mortars.

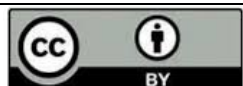
## 1. Introduction

Every tonne of Portland cement clinker produced releases roughly a tonne of CO<sub>2</sub> into the atmosphere. Multiply that by the billions of tonnes manufactured each year and it becomes clear why the construction industry's search for lower-carbon binders is not a peripheral concern but a central one [1]. Against this backdrop, lime and GGBS have attracted growing interest — not as novelties, but as a return to materials with deep historical roots and, as it turns out, impressive technical credentials when used together.

Lime mortars need no introduction to anyone working in historic masonry conservation. Builders have been mixing lime, sand, and water for thousands of years, and the properties that made these mortars so durable — breathability, flexibility, and compatibility with soft masonry units — are the same ones that make them attractive for modern sustainable construction [2]. The problem, of course, is that pure air lime sets slowly through carbonation, meaning early-age strength is low and freshly laid masonry is vulnerable. Natural Hydraulic Limes (NHL) go some way toward addressing this, offering a faster hydraulic set, but they still fall short of OPC in many structural applications [3].

This is where GGBS enters the picture. A by-product of iron manufacturing, GGBS is a latent hydraulic material that does very little on its own, but in the presence of the calcium hydroxide released during lime hydration, it undergoes a pozzolanic reaction to form additional calcium silicate hydrate (C-S-H) gel — the same binding phase responsible for strength in cement paste [4]. The lime-GGBS system is therefore not an arbitrary combination: lime provides the alkaline trigger, GGBS provides the reactive silica and alumina, and together they generate a denser, stronger, more durable mortar than either component alone.

What is missing from the literature, however, is a critical and systematic review of how well this combination actually performs across all relevant parameters. Most existing reviews either focus on pure lime systems or evaluate GGBS exclusively in cementitious contexts. This paper fills that gap, synthesising the available experimental evidence and subjecting it to critical scrutiny rather than simply cataloguing results.



## 2. Materials: Composition and Properties

### 2.1 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is produced by rapidly quenching molten blast furnace slag — a by-product of iron smelting — with water or air. The rapid cooling produces a glassy, amorphous material rather than the crystalline phases that would form under slow cooling, and it is this amorphous structure that gives GGBS its reactivity [6]. XRD analyses of unreacted GGBS consistently show the broad diffuse hump characteristic of amorphous material, with minimal crystalline peaks. Chemically, GGBS is dominated by CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and MgO, with CaO content typically between 38 and 45%. Its specific surface area of around 400–450 m<sup>2</sup>/kg provides a large reaction surface, and its 28-day strength activity index exceeds 92% relative to OPC — a standard measure of pozzolanic performance.

From an environmental perspective, GGBS is classified as an industrial by-product under most Product Category Rules. Its embodied CO<sub>2</sub> of approximately 0.07 kg per kg is more than ten times lower than OPC, making it one of the most carbon-efficient binder materials available for construction [7].

### 2.2 Lime types used in mortar systems

#### 2.2.1 Non-hydraulic (air) lime

Non-hydraulic lime — whether as lime putty or hydrated powder — sets exclusively through carbonation, the slow uptake of atmospheric CO<sub>2</sub> to reform calcium carbonate. It provides an abundant alkaline environment (Ca(OH)<sub>2</sub>) to activate GGBS, but contributes almost nothing to early mechanical strength on its own [7]. Lime putty typically contains around 89% calcium hydroxide and 11% calcium carbonate, and the slow setting kinetics that characterise these systems are both their greatest limitation and, paradoxically, one of the properties that makes them so compatible with historic masonry [7].

#### 2.2.2 Natural Hydraulic Lime (NHL)

Produced by calcining argillaceous or siliceous limestones at around 900°C, NHL contains calcium silicates and aluminates alongside free lime, enabling both hydraulic setting and carbonation. NHL5, with its higher hydraulic content, achieves meaningfully faster early strength development than NHL3.5 and is the more relevant grade for structural masonry mortars. European Standard EN 459-1:2010 provides the governing classification framework [3].

#### 2.2.3 Hydrated lime (HL) in ternary systems

Commercial hydrated lime (Ca(OH)<sub>2</sub> powder) appears in the literature primarily as a partial OPC replacement in ternary systems alongside GGBS. Its role here is dual: it provides additional alkaline activation for GGBS and consumes surplus portlandite — the weakest crystalline phase in hardened cementitious paste — converting it into strength-contributing C-S-H gel. These distinctions between lime types are not academic: they run through the entire literature and must be kept in mind when comparing results across studies.

## 3. Fresh properties and workability

Workability is the practical gateway to everything else. A mortar that is difficult to place, or that bleeds and segregates, will underperform regardless of how impressive its 28-day strength turns out to be. The workability of lime–GGBS

mortars has attracted reasonable attention in the literature [2], though the picture is complicated by the fact that different studies use different test methods and different approaches to mix proportioning.

The most thorough dataset on non-hydraulic lime–GGBS mortars comes from Ahmed et al., who maintained consistent workability across mixes by adjusting water content to achieve a constant 10 mm ball penetration depth per BS 5628 [7]. This is a sensible approach for ensuring comparable placement quality, but it means that different GGBS replacement levels correspond to different water-binder ratios — a confounding variable that makes it difficult to isolate the effect of GGBS content on strength independently of mix water. This methodological point applies, to varying degrees, across several studies in this review.

In ternary systems, GGBS particles are glassy and angular, and replacing OPC with GGBS at comparable fineness tends to reduce water demand slightly, owing to the lubricating effect of the vitreous particle surfaces. This contrasts with highly reactive supplementary materials such as silica fume, which substantially increase water demand [4]. The addition of Calcined Sea Shell Powder in quaternary binder systems, however, increased water demand and reduced slump flow — a reminder that workability effects are system-specific and cannot be assumed to transfer from one mix composition to another.

On setting time, the critical question for pure air lime–GGBS mortars is whether they set quickly enough for practical construction. Ahmed et al. [7] confirmed that mortars with 10–16% GGBS meet BS 5628 compliance within 28 days, with 10% GGBS sufficient to attain the highest strength designation. From a practical standpoint, this is perhaps the most immediately significant fresh-state finding in the literature: it demonstrates that cement-free lime–GGBS mortars can be used on a real construction site without the excessively slow setting that has historically limited pure air lime systems.

## 4. Mechanical properties

The mechanical performance data in this field are broadly consistent and, taken together, make a compelling case for GGBS as a strength enhancer in lime mortar systems. However, the raw numbers require careful contextualisation before firm conclusions can be drawn.

### 4.1 Compressive strength

#### 4.1.1 Binary non-hydraulic lime–GGBS system

The most thoroughly documented dataset for this system was reported by Ahmed et al. [7], who investigated non-hydraulic lime putty mortars at a 1:3 binder-to-sand ratio with GGBS additions of 0%, 10%, 14%, and 16% by total mix weight. Plain lime putty mortar without GGBS failed to meet BS 5628 Designation (i) at 28 days. With 10% GGBS, the mortar met Designation (i), confirming the minimum effective GGBS threshold. At 16% GGBS, the mortar comfortably satisfied all four BS 5628 strength designations. The underlying mechanism is the pozzolanic reaction between GGBS's latent hydraulic phases and the Ca(OH)<sub>2</sub> in the lime putty, gradually generating C-S-H gel as the system matures.

#### 4.1.2 Natural Hydraulic Lime (NHL5)–GGBS system

The most striking result in the binder literature is the 125% compressive strength increase achieved by replacing

20% of NHL5 with GGBS at 28 days. This figure is mechanistically credible: NHL5 hydration produces both early C-S-H and significant Ca(OH)<sub>2</sub>, providing ample alkaline activation for GGBS. The pozzolanic reaction then converts portlandite — otherwise a weak link in the microstructure — into additional strength-contributing C-S-H gel. It is worth noting, however, that the baseline compressive strength of plain NHL5 mortar is modest (typically 2–4 MPa at 28 days), so a 125% increase, while technically impressive, still leaves the resulting strength well below that of OPC mortar. The practical relevance of this result therefore depends entirely on the intended application [3].

#### 4.1.3 Ternary OPC-GGBS-hydrated lime system

Dhanesh and Shanmugasundaram's [5] investigation of ternary binder systems produced the highest absolute strengths

in the reviewed literature. The optimum mix — OPC 60%, GGBS 30%, hydrated lime 10%, at a water-binder ratio of 0.36 — achieved 56.20 MPa compressive strength, 5.58 MPa flexural strength, and 4.25 MPa split tensile strength at 28 days. These are strong results by any standard. The dual mechanism here combines GGBS's latent hydraulic activity with hydrated lime consuming surplus portlandite, generating supplementary C-S-H and calcium aluminate hydrate (C-A-H) gel that densifies the paste matrix and strengthens the interfacial transition zone.

One critical observation, however, deserves to be made plainly: these mixes still contain 60% OPC. That is not a minor detail. The sustainability credentials of this system, while genuine, are meaningfully weaker than those of binary lime-GGBS formulations, and the performance data should be interpreted with that in mind [5].

**Table 1:** Summary of compressive, flexural, and split tensile strength data for lime-GGBS mortar systems from reviewed literature.

Binder system	GGBS level	fc 28d (MPa)	Flexural (MPa)	Split tensile (MPa)	Ref.
Air lime putty + GGBS	0% (control)	< 1.5 (Desig. IV)	—	—	[3]
Air lime putty + GGBS	10%	Desig. (i) met	—	—	[3]
Air lime putty + GGBS	16%	Desig. (i)–(iv)	—	—	[3]
NHL5 + GGBS	20%	+125% vs. control	Enhanced	—	[3]
OPC+GGBS+HL (ternary)	30% GGBS + 10% HL	<b>56.20 MPa</b>	<b>5.58 MPa</b>	<b>4.25 MPa</b>	[5]
Bio-brick + HL mortar	N/A	+7.9% vs. conv.	Shear +12.6%	—	[8]
Hydrated lime UHPC mortar	Supplementary HL	> 177 MPa (combined)	> 7.3 MPa	—	[9]

#### 4.2 Flexural strength and porosity

Flexural strength and porosity are closely correlated with compressive strength in these systems [7]. The NHL5-GGBS literature confirms that both compressive and flexural strength improve with increasing GGBS content up to the 20% optimum, with the pozzolanic reaction reducing total porosity through secondary C-S-H infilling of capillary pores. One nuance worth noting: at the masonry system level, increasing mortar stiffness can reduce bond ductility between mortar and masonry unit [3]. This is a system-level consideration that the existing literature which focuses almost exclusively on mortar prism testing has not adequately addressed.

### 5. Durability Performance

Strength at 28 days tells only part of the story. A mortar that performs well mechanically but deteriorates rapidly under exposure to moisture, sulphates, or cyclic wetting and drying will fail in practice, and the durability data for lime-GGBS systems are therefore as important as the strength data arguably more so for heritage conservation applications where mortars are expected to perform for decades without replacement.

#### 5.1 Water absorption and capillary suction

The evidence here is clear and consistent. GGBS additions reduce both water absorption and capillary suction in lime mortar systems, with the mechanism straightforward [7]: the pozzolanic reaction generates C-S-H gel that fills capillary pores, reducing both total porosity and the connectivity of the pore network. Studies on NHL5-GGBS and non-hydraulic lime-GGBS systems confirm this, with porosity reductions correlating directly with increasing GGBS content [3]. This is not a surprising finding, but its experimental confirmation across multiple independent studies is important for building confidence in the result.

#### 5.2 Sulphate resistance

Lime-GGBS systems have a structural advantage over OPC-rich mortars when it comes to sulphate resistance. High aluminate content in OPC paste is the primary driver of ettringite formation under sulphate attack - a phase whose expansive crystallisation causes progressive paste disintegration. GGBS-rich systems have substantially lower aluminate content, reducing the available reactant for this damaging reaction. XRD analysis of NHL mortar systems after Na<sub>2</sub>SO<sub>4</sub> immersion confirms ettringite as the dominant deterioration product, with GGBS-containing systems showing reduced phase formation at equivalent exposure durations [10].

Critically, wetting-drying cycling in sulphate solution was found to produce more severe microstructural damage than static immersion, a result with direct design implications for mortars in exposed outdoor masonry. This finding has not yet been specifically evaluated for binary lime-GGBS formulations, which is a gap that carries practical significance.

#### 5.3 Chloride penetration

The chloride data in the lime-GGBS literature are largely indirect, drawn from analogous geopolymer GGBS and ternary concrete systems rather than from binary lime-GGBS mortars directly. This is a gap. The underlying mechanism GGBS aluminate phases chemically binding chloride as Friedel's salt, confirmed by XRD is well-established, and the 50.6% reduction in chloride penetration reported for ternary OPC-GGBS-hydrated lime concrete provides strong supportive evidence. But direct RCPT or chloride diffusion testing on binary lime-GGBS mortars has not been reported, and it should be [11,12].

#### 5.4 Freeze-thaw and carbonation

Lime-based mortars are historically recognised for their superior freeze-thaw resistance compared with brittle cement

mortars, a consequence of their inherent flexibility and capacity to accommodate micro-cracking without catastrophic failure [2]. The specific influence of GGBS on this behaviour in lime mortar systems has not, however, been experimentally measured, which is a notable omission given the relevance of freeze-thaw performance for external masonry in temperate and cold climates. Similarly, carbonation depth measurement in lime-GGBS systems has not been systematically reported. These represent two of the more significant practical gaps in the existing literature.

## 6. Microstructural analysis

The microstructural evidence in this field is some of the most satisfying in the literature, because it provides a coherent mechanistic narrative that explains the mechanical and durability data rather than simply adding to them. XRD, SEM, TGA, MIP, and FTIR analyses across multiple independent research groups tell a consistent story.

### 6.1 XRD phase evolution

XRD analysis of unreacted GGBS the natural starting point for any microstructural account consistently shows the broad amorphous hump of glassy material, with minimal crystalline peaks [6]. As hydration and pozzolanic reactions proceed in lime-GGBS systems, the XRD pattern evolves in a predictable and mechanistically meaningful way. Portlandite peaks diminish as pozzolanic consumption proceeds. Broad C-S-H peaks emerge, reflecting the poorly crystalline nature of the gel. In NHL systems, calcite peaks appear alongside hydraulic products, reflecting parallel carbonation [9].

The rate of portlandite consumption is a particularly useful proxy for pozzolanic reaction extent. Studies on ternary OPC-GGBS-hydrated lime systems confirm that increasing GGBS and HL content accelerates portlandite depletion, with portlandite peaks becoming weak or absent at later curing ages in optimised mixes. Since portlandite is the weakest phase in hardened cementitious paste large, poorly bonded, preferentially cleaved under load its progressive conversion to C-S-H represents a genuine net improvement in microstructural quality, not just a change in phase assemblage.

XRD analysis of systems exposed to sulphate attack further confirms ettringite and gypsum as the primary deterioration products, with GGBS-containing systems showing reduced crystalline phase formation — consistent with the durability findings [10].

### 6.2 SEM morphology

SEM images tell a complementary and visually compelling story. Unreacted GGBS particles are angular and glassy with sharp edges. Post-hydration, partially dissolved GGBS particles are surrounded by C-S-H gel that bridges the interparticle space and begins to bind aggregate surfaces. In optimised mixes, the interfacial transition zone often the weakest link in cementitious composites is visibly densified, with C-S-H and C-A-H gel reducing the width and porosity of the aggregate-paste interface compared with lime-only controls [6].

MIP confirms the macroscopic consequence of this microstructural refinement: reduced critical pore diameter and lower total porosity in GGBS-containing systems. The convergence of SEM imaging and MIP data across multiple studies gives confidence that the observed strength and

durability improvements are genuinely attributable to microstructural densification rather than mix composition artefacts [9].

## 6.3 TGA and FTIR analysis

TGA analysis in hardened lime-GGBS mortars quantifies residual portlandite content (dehydration peak near 450°C), carbonate content from carbonation (decomposition near 700°C), and bound water in C-S-H gel (broad thermal events below 200°C)[6]. The progressive reduction in portlandite content with curing age, confirmed by TGA across multiple studies, provides independent corroboration of the XRD evidence and confirms that the pozzolanic reaction continues well beyond 28 days an important point given that most mechanical testing stops there. FTIR spectroscopy confirms the presence of Si-O-T stretching bands characteristic of C-S-H and geopolymeric gel networks, and the observed shift in the Si-O-Al band with increasing GGBS content reflects aluminium incorporation into the gel structure, a feature associated with improved chloride binding and long-term chemical stability.

## 7. Sustainability and environmental assessment

The environmental case for lime-GGBS mortars is, in many respects, the strongest part of the story and also the part most in need of more rigorous quantification.

### 7.1 Embodied carbon comparison

The basic facts are well-established. OPC clinker production releases approximately 0.83 kg CO<sub>2</sub> per kg of material, making it one of the most carbon-intensive materials in widespread use. Hydrated lime carries a similar embodied carbon intensity of around 0.75 kg CO<sub>2</sub>/kg, though this figure is partially offset by CO<sub>2</sub> re-sequestration through carbonation over the mortar's service life a factor that static embodied carbon calculations routinely ignore. GGBS, classified as an industrial by-product, carries an embodied CO<sub>2</sub> of approximately 0.07 kg/kg more than ten times lower than OPC. The arithmetic is compelling: a mortar in which GGBS replaces a significant proportion of the lime or OPC binder will carry substantially lower embodied carbon, with published estimates suggesting savings of 30–55% depending on system type and replacement level [7].

What makes this particularly significant is that the sustainability argument does not require any trade-off with performance. The mechanical and durability data reviewed in earlier sections confirm that lime-GGBS systems can match or exceed OPC-based equivalents in many applications. This is relatively unusual in sustainable materials research, where performance compromises are common. The caveat is that the full life cycle data are incomplete — no comprehensive cradle-to-grave LCA has been published specifically for binary lime-GGBS mortar systems, and closing that gap is a priority for future research.

### 7.2 Alignment with global sustainability frameworks

- UNEP Sustainable Buildings and Climate Initiative — promoting low-carbon construction materials in the built environment.
- Paris Agreement (2015) — targets for net-zero embodied carbon in building materials by 2050.

- Circular Economy Principles — GGBS valorises a material that would otherwise require energy-intensive disposal.
- European Green Deal — regulatory targets for carbon-neutral construction by 2030.

### 7.3 Sustainability trade-offs in ternary systems

It is important to be clear-eyed about the limits of the sustainability case for ternary OPC–GGBS–hydrated lime systems. The optimum ternary mix reviewed here contains 60% OPC, which substantially reduces the carbon saving relative to binary alternatives [3]. The strength performance of ternary systems is higher in absolute terms, but researchers and practitioners need to decide whether that performance gain justifies the sustainability cost. For heritage conservation and low-rise residential masonry where binary lime–GGBS mortars can meet structural requirements the case for retaining 60% OPC is weak. For demanding structural applications where 56 MPa compressive strength is genuinely required, the ternary system may be the appropriate choice.

## 8. Critical analysis

Any honest review of this field has to acknowledge that the evidence base, while promising, is thinner than it first appears. Several issues recur across the literature and deserve to be stated plainly.

### 8.1 Methodological inconsistencies

The most persistent problem is the lack of standardisation. Studies use different water–binder ratios, different curing conditions, different aggregate types and gradings, and different test methods sometimes with no apparent awareness of how much these choices affect the results [7]. The dropping-ball workability test used by some researchers is not recognised in international standards, making cross-study comparisons unreliable. Curing humidity and temperature affect carbonation rates significantly in lime systems, yet these variables are often reported only in passing. Until the field adopts consistent testing protocols referenced to EN 1015 or equivalent standards, it will be difficult to build a robust quantitative picture that practitioners can rely on.

The strength claims also deserve scrutiny. The 125% compressive strength increase for 20% GGBS in NHL5 is the headline result in the binary literature, and it is credible — but a 125% increase from a baseline of 2–3 MPa yields an absolute strength of approximately 4.5–6.75 MPa, which is adequate for many masonry applications but not exceptional in engineering terms. The more practically significant finding may be the BS 5628 compliance data: the confirmation that 10–16% GGBS in non-hydraulic lime mortars meets all strength designations at 28 days is directly actionable and has immediate implications for low-carbon masonry construction.

## 9. Applications and industrial relevance

### 9.1 Heritage and historic masonry conservation

The most established application is the repair and restoration of historic masonry, and it is here that lime–GGBS mortars offer the most immediate and least controversial value proposition. Non-hydraulic lime mortars are the standard repair material for historic structures on grounds of breathability, flexibility, reversibility, and compatibility with soft historic substrates. The addition of GGBS enhances

strength without fundamentally altering these compatibility properties, making GGBS-enhanced lime mortars a technologically advanced yet historically sensitive option that conservation practitioners can use with confidence.

### 9.2 Sustainable new-build masonry

The demonstrated BS 5628 compliance of lime–GGBS mortars confirms their viability for new-build load-bearing masonry construction without cement. In the context of tightening embodied carbon targets the UK Green Building Council's net-zero whole life carbon roadmap, the RIBA 2030 Climate Challenge, and equivalent frameworks internationally the 30% + embodied carbon saving over cement-based equivalents is a meaningful and practically achievable benefit that does not require any performance compromise.

### 9.3 Stabilised earth block masonry

An emerging and largely uninvestigated application is as a bedding mortar for stabilised mud block (SMB) or Compressed Stabilised Earth Block (CSEB) masonry. The material compatibility between lime-stabilised blocks and lime–GGBS mortars is intuitively strong, and the combination would constitute a holistic low-carbon masonry system with the potential for both embodied carbon and cost savings in low-rise housing construction, particularly in contexts where locally sourced soils and industrial by-products are available. This is, at present, an unexplored opportunity.

## 10. Conclusions

The literature reviewed here supports a cautiously optimistic assessment of lime–GGBS mortars. The evidence for strength enhancement is consistent and mechanistically well-explained. The durability data, while less complete, point in the same direction. The sustainability case is strong on paper, though it requires better life cycle analysis support to be fully convincing. Several clear conclusions emerge.

- GGBS additions of 10–16% to non-hydraulic lime mortars are sufficient to meet all four BS 5628 strength designations at 28 days — a finding with immediate practical implications for low-carbon, cement-free masonry construction.
- Replacing 20% of NHL5 with GGBS delivers the highest reported strength enhancement in binary systems (+125% at 28 days), driven by the pozzolanic conversion of portlandite to C-S-H gel in an NHL-activated environment.
- Ternary OPC–GGBS–hydrated lime systems achieve high absolute strengths (56.20 MPa compressive) and offer genuine carbon savings over OPC-only systems, though the presence of 60% OPC limits their sustainability credentials relative to binary alternatives.
- Microstructural evidence from XRD, SEM, TGA, and MIP is coherent and consistent across multiple independent studies: portlandite consumption, C-S-H densification, and ITZ improvement are the three dominant mechanisms driving performance improvement.
- Durability is enhanced in GGBS-containing systems through microstructural densification, improved sulphate resistance, and reduced chloride penetration (up to 50.6% in analogous ternary systems), though direct testing on binary lime–GGBS mortars remains limited.
- Embodied CO<sub>2</sub> savings of 30–55% compared with OPC-based equivalents make lime–GGBS mortars a credible and

technically supported pathway toward net-zero masonry construction.

- The most significant research priorities are long-term performance data beyond 90 days, masonry bond strength testing, standardised mix design protocols, comprehensive LCA, and investigation of lime–GGBS as a bedding mortar for stabilised earth block construction.
- The materials are promising. The mechanisms are well understood. What the field now needs is more systematic, long-term, standardised experimental data to turn that promise into confident engineering practice.

### Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

### Conflicts of interest

The author declares no conflict of interest.

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No new data were created.

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