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Academic Journal of
European University of Bangladesh

Effects of Proportional Replacement of Cement by Waste Eggshells to Understand Cementitious Materials Properties

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Received: December 15, 2025
Revised: April 3, 2026
Accepted: April 7, 2026

Abstract

Concrete is now the most widely used construction material and its production has exceeded the number of all other building materials combined because of rapid infrastructural development. This study presents an investigation into the use of eggshell powder as a partial replacement of cement in concrete: an effort to positively impact the cost reduction and environmental issues within construction. In the analysis, eggshell powder (ES) is used as 2.5%, 5%, and 10% of alternative material to Ordinary Portland Cement (OPC) in a mixture of concrete and the compressive strength of the concrete at different curing periods of 7, 14, 21, and 28 days is examined. The findings indicated a reduction in compressive strength as the substitution level of eggshell powder increased and the 10% replacement mix had been clearly associated with a significant decrease in strength. However, lower admixture replacements (2.5% and 5%) yielded enough strength for low strength uses. The specific gravity of the concrete decreased with the use of eggshell powder. It can be used for lightweight applications, such as paving blocks and temporary structures. This study also explored the economic and environmental benefits in Bangladesh of using eggshell powder, showing that it could reduce construction costs by saving up to 1.156 billion taka in cement expenses, while also reducing the environmental impact by recycling 115,600 tons of eggshell waste per year. This paper shows the potential of eggshell powder as an eco-friendly and low-cost cement replacement to aid in resource sustainability and environmental protection from waste disposal, advocating sustainable construction.

Keywords: *Cement replacement, eggshell powder, compressive strength, waste material, sustainable concrete*

1. Introduction

Global demand for concrete and cementitious materials is tremendous and the world production of cement alone is about 4.1 billion tons per annum [1]. This underlines the need for sustainable and alternative building materials. Making a large amount of concrete to meet the demand of the world will require about 2.62

billion tons of cement, 13.12 billion tons of aggregate, and 1.75 billion tons water [2]. In 2020, the total global production of concrete remained at 26Gt/year, where approximately 4Gt is accounted to cement, which demands ca.20Gt of virgin aggregates and billions of tons of water for infrastructure [2]. This illustrates the enormous reliance of human societies on concrete. Cement is widely used as a binder in the formation of concrete. There are extensive applications for cement in infrastructure, offices, apartments and large construction activities [3]. However, approximately 5% of total world CO_2 emissions have been attributed to world cement production [4].

Bangladesh Cement sector annually deposits onto land about 0.03% toxic chemical substances and into air 0.01%, releases SO_2 pollutants at the rate of 10.42 %, and total particulates at the rate of 8.49%. Most of these substances are destructive for human health, especially worker's health in the industry. However, in view of increasing ecological pressures, other important is an attempt to estimate the negative influence of cement production on the atmospheric-air and workers' health [5]. One option for reducing the dependence on cement in construction through increasing the use of alternative materials might have a potential to reduce the negative consequences. On the other hand, if new materials with the preferable material and chemical properties of a required cement can be produced as an additive to already existing cement, it will minimize the exploitation of natural resources, the CO_2 in the atmosphere will reduce its concentration, and constructions' ecofriendly behavior can also be promoted [6].

A new substitute material to meet the high demands for building material is eggshell powder. This was identified via current research. The powdered form of eggshells poses a significant problem of solid waste to the environment since the material was produced in massive quantities around the world. Even though the eggshell itself may not be a source of toxic substances to the environment, the creation of waste in the form of solids poses a significant problem when its disposal goes to the landfill since the material tends to decompose and pollute the soil. Additionally, the material poses a health risk when decomposed in the open.

Partial replacement of cement with eggshell powder has received increasing attention on account of its high content of calcium carbonate ($CaCO_3$),for an improved sustainability and mechanical strength of concrete [7]. This material is capable of being calcined to calcium oxide (CaO). A significant proportion of Portland cement consists of calcium oxide (CaO). The use of eggshell in concrete production could have an important role to play when it comes to mitigating the adverse impacts from cement manufacture [8]. Moreover, the use of eggshell also cuts back on municipal waste production.

The demand of replacing such an environmental hazardous process by a sustainable one for the industry also motivated to perform this study. Due to the limitation of natural resources and rapid emission of CO_2 into atmosphere, there is an increasing urgency on green building activity in construction industry [9]. Surely, cement application for making concrete is also a kind of pollution to nature. 4.12 The problem of cement production in the world To have an idea about the dimension of a global problem generated by the world production of cement, this industry is responsible for releasing around 7% of all CO_2 gas on earth [10]. Concurrently, the urbanization of this planet has also put a great impact on solid waste generation.

The eggshell wastes are numerous in countries where the poultry industry is developed. For example, Pakistan lays approximately 17.5 billion eggs annually [11]. Owing to the relatively higher proportion of eggshells (about 11%) in the entire weight of an egg [12], landfilling presents a number of significant environmental problems as far as components are concerned. Furthermore, discarding of eggshells accounts substantially to the increase in landfill sites worldwide [13]. It should be noted that both the elemental composition and structure of eggshell is found to contain calcium carbonate which makes it a potential source of CaO after being calcined and can be compared with the conventional cementitious binders [14]. This increases the necessity of further investigations on eggshell powder as an abrasive. Some investigations [15] [16] have revealed that partial substitution is feasible without any marked reduction in the strength of the material. Most studies employed low strength concrete. Little research has been conducted with high-strength concrete mixtures.

The purpose of this research is to investigate the strength of concrete by replacing eggshell powder instead of cement in mix design which may be applied in low strength structure. Although the addition of eggshell powder led to a reduction in concrete strength compared to the control mix, the primary objective of this study is to explore sustainable and eco-friendly alternatives for partial cement replacement. Eggshell powder is an abundant waste material, and its incorporation helps reduce cement consumption and associated carbon emissions, promoting environmental sustainability. The resulting concrete still meets the requirements for low-strength structural applications, such as non-load-bearing walls, pavements, or sidewalks, where ultra-high strength is not critical. Thus, the use of eggshell powder provides a practical way to combine waste valorization with sustainable construction practices. This further research will control compressive, tensile and flexural strength in order to reinforce the mixture of concrete containing eggshell powder at that standardized rate.

2. Materials and Methods

2.1 Materials

To guarantee experiment reproducibility and to give a comprehensive understanding of their qualities and origins, the materials utilized in this investigation are explained in depth in this section.

2.1.1 Cement

The primary binder in all mixtures was Ordinary Portland Cement (OPC) type ASTM C150. Before use, the chemical and physical properties of Portland cement used in the experiments were tested to ensure that they met their standard requirements. The Portland cement was also kept in an air-tight container so as not to absorb moisture and lumps from forming.

2.1.2 Eggshell Powder

The eggshells (ES) were collected from households, restaurants, poultry farms and duck farms to cover a variegate of ES sources. The egg shells were cleaned physically to remove any residual organic materials and left for drying under natural condition up to 48 hours. The dried eggshells were crushed to the fine powder using wooden hammer so that no metal particle might be mixed with material, as shown in Figure 1. To ensure particle sizes closer to the powdered material (cement) for good blending in concrete, fine sieving of the powdered eggshells was carried out. These 100% eggshells powders were then substituted for the whole cement mass, at 2.5, 5 and 10%. A study conducted by Ngayakamo (2025) [18] investigated the use of eggshell powder as an eco-friendly partial replacement for cement in mortar. The researcher examined the effects of incorporating 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% eggshell powder on the performance of the mortar. This study was guided by the methodology and findings reported by Ngayakamo (2025) [18].

2.1.3 Fine Aggregate (Sand)

The fine aggregate in all the concrete mixes conforms to Natural River sand. The sand had a fineness modulus (FM) of 2.64, specific gravity 2.62, and water absorption capacity of 1.1%. All physical properties for the sand material were determined following the ASTM C128 & ASTM C33 standards. Other characteristics of the sand material showed no organic content and over abundant amounts of silt.

2.1.4 Coarse Aggregate

In this study natural stone chips was used as coarse aggregate. The natural stone aggregates used in the research were collected from savar. These aggregates passed the 16 mm sieve. The physical characteristics of the coarse aggregates including specific gravity, water absorption, bulk density and Los Angeles abrasion values, were determined in accordance with ASTM C128, ASTM C29 and ASTM C131 standards.

Figure 1: Eggshell and Eggshell Powder

2.2 Methods

The testing protocols, analytical techniques and experimental procedures are described in the following section.

2.2.1 Preparation of Eggshell Powder-C

Eggshell powder was used to partially replace Ordinary Portland Cement (OPC) at replacement levels of 2.5%, 5% and 10% by weight of the total binder content. In this study, the eggshells were washed, dried, and then ground manually using a mortar and pestle followed by sieving through a specific mesh size (e.g., 75 µm) to ensure a reasonably uniform particle size for use as cement replacement. We acknowledge that more controlled methods, such as ball milling, can provide finer and more uniform particles. However, the chosen method was selected for simplicity, cost-effectiveness, and reproducibility under standard laboratory conditions. Additionally, previous studies (e.g., Ngayakamo, 2025) have shown that sieving after manual grinding can produce particle sizes suitable for cementitious applications without significant compromise in performance. The exact dosage of ES was weighed and pre-mixed in dry condition with OPC to obtain a homogeneous distribution of the ES. This was mixed in a concoction machine for 3-5 min such that it changes in color. This technique is also important due to the fact that well-milled ES has been proved to take part in the hydration process of cement paste that could cause increase in concrete strength.

2.2.2 Concrete Mixing

The concrete mixing was carried out in acquiescence with ASTM C192/C192M shown in Figure 2. The concrete mixing steps included drying mixing process, binder addition, water and admixture addition.

Dry Mixing Process: The coarse and fine aggregates were mixed for a period of 2 minutes.
Binder Addition: The cement-eggshell powder was in turn mixed with the aggregate. Next, the mass was mixed for a further 2 minutes.
Water and Admixture Addition: Water, and if used, the superplasticizer was added in divided portions. MIXING was continued for 3.5 more minutes to the point the mixture was sufficiently wet to a homogeneous consistency of fresh mix.
A slump test was conducted for every mix to check the workability. The dosage of the super plasticizer was adjusted when required to maintain a target slump of 100 ± 10mm

Figure 2: Mortar mixing for Cylinder

2.2.3 Casting & Curing of Specimens

The concrete was cast in the cylindrical molds (dia 100 mm and depth 200 mm) with three layers. Tamp it down 25 times for the number of layers to eliminate air. Wet jute bags were kept on the specimens for curing after casting of concrete. The sample was de-molded after 24 hours of casting. The jute bags which were wet, had an edge on retaining of moisture for the concrete. These cubes were kept in a potable water storage tank with temperature 23 ± 2°C while curing of specimen was done at ages for testing varied between 3, 7, 14, 21 and 28 days. A sample of curing process is shown in Figure 3.

Figure 3: Cylinders under curing process

Figure 4: Concrete specimen testing under

2.2.4 Compressive Strength

The compressive strength was tested according to ASTM C39/C39M. All the age of test were conducted on three specimens for each mix. The test was conducted in a universal testing machine at a feed rate of 0.25 MPa/s with compressive strength (σ) computed by the following equation:

$$\sigma = \frac{P}{A} \qquad (1)$$

The equation express σ is the Compressive Strength (MPa), P is the Maximum Failure Load recorded (N), A is the Cross-sectional Area of the cylindrical specimen (mm^2).
The test ages were plotted to determine the effects of the replacement of the ES contents of the aggregate on the early- and late-age strength of the mix. A sample of concrete specimen testing under UTM is shown in Figure 4.

3. Results & Discussion

Compressive strength of the concrete cylinders having various eggshell powder contents (2.5, 5 or 10%, where used as a replacement for the cement) was determined at age of 7, 14, 21 and 28 days describe in this section.

3.1 Compressive Strength Results

The findings of 7 days' compressive strength are presented in Table 1. Control Concrete (0% Eggshell) Development Compressive strength of 3000 Psi was observed in the control concrete during day 7 testing, whereas those containing 2.5%, 5% and 10% eggshell have shown compressive strengths of 2700 psi, 2400 psi and 2100 psi, respectively. Such an early drop in strength is related to greater porosity and lower binding ability of eggshell powder.

Table 1: 7 Days Compressive Strength (PSI)

Contents	Cylinder Number [Ratio 1:2:4]	Total Mater-ials (kg)	Cement (kg)	Eggshell (kg)	Sylheti Sand (kg)	¾' Down Stone (kg)	Water [Water Cement Ratio 0.5]	Loads (KN)	Compr-essive Strength (PSI)
C-0%	1	3.5	0.500	0	1	2	0.5	162.5	3000
C-2.5%			0.488	0.0125				35.00	2700
C-5%			0.475	0.025				146.25	2400
C-10%			0.450	0.05				113.75	2100

The compressive strength after 14 days of different proportion of ES are presented in Table 2. Results reveal, The Control sample gave 3600 psi compressive strength. The corresponding results for the 2.5%, 5%, and 10% ES mixes were 3240 psi, 2880 psi and 2520 psi, respectively. The gradual decrease in strength is consistent with the eggshell powder's increased porosity and decreased cement content. Eggshell powder is less finely ground than materials like cement or other pozzolans, which can impact its effectiveness in the reaction with calcium hydroxide and decrease its compressive strength.

Table 2: 14 Days Compressive Strength (PSI)

Contents	Cylinder Number [Ratio 1:2:4]	Total Materials (kg)	Cement (kg)	Eggshell (kg)	Sylheti Sand (kg)	¾' Down Stone (kg)	Water [Water Cement Ratio 0.5]	Loads (KN)	Compressive Strength (PSI)
C-0%	1	3.5	0.500	0	1	2	0.5	195	3600
C-2.5%			0.488	0.0125				175.5	3240
C-5%			0.475	0.025				156	2880
C-10%			0.450	0.05				136.5	2520

The compressive strength after 21 days of different proportion of ES are presented in Table 3. Results reveal, The Control sample gave maximum strength 3600 psi. The gradual decrease in strength is consistent with the eggshell powder's increased porosity and decreased cement content.

Table 3: 21 Days Compressive Strength (PSI)

Contents	Cylinder Number [Ratio 1:2:4]	Total Materials (kg)	Cement (kg)	Eggshell (kg)	Sylheti Sand (kg)	¾' Down Stone (kg)	Water [Water Cement Ratio 0.5]	Loads (KN)	Compressive Strength (PSI)
C-0%	1	3.5	0.500	0	1	2	0.5	205.82	3800
C-2.5%			0.488	0.0125				185.25	3420
C-5%			0.475	0.025				165.66	3040
C-10%			0.450	0.05				144	2660

The compressive strength after 28 days of different proportion of ES are presented in Table 4. Result reveals, 4000 psi strength was gained by control specimen. Table 4 represents Moderate reductions were seen in the 2.5% and 10% replacement mixes, which recorded 3600 psi and 2800 psi, respectively.

Table 4: 28 Days Compressive Strength (PSI)

Contents	Cylinder Number [Ratio 1:2:4]	Total Materials (kg)	Cement (kg)	Eggshell (kg)	Sylheti Sand (kg)	¾' Down Stone (kg)	Water [Water Cement Ratio 0.5]	Loads (KN)	Compressive Strength (PSI)
C-0%	1	3.5	0.500	0	1	2	0.5	216.67	4000
C-2.5%			0.488	0.0125				195	3600
C-5%			0.475	0.025				173.33	3200
C-10%			0.450	0.05				152	2800

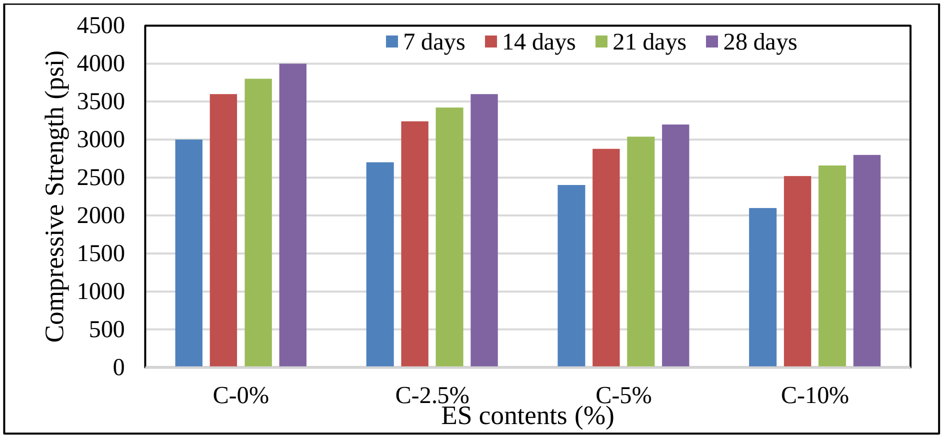

Figure 5: Compressive Strength (PSI) of different ES content

The compressive strength of different ES content of 7, 14, 21 and 28 days are shown in Figure 5. According to the overall analyses, eggshell powder reduces the compressive strength at all ages even though moderate replacement ratio (2.5–5%) still have acceptable strength values for low-strength applications. The greatest reduction was in the 10% replacement that has more internal voids and less calcium. The eggshell powder is not grind as fine other more expensive materials such as cement or certain pozzolans which may also have impact on the its level of effectiveness in reaction with $Ca(OH)_2$.

3.2 Normal Consistency and Setting Time

The typical consistency and setting time results of 2.5%, 5% and 10% eggshell powder are presented in Tables 5-7. The eggshell particle has irregular and porous surface, therefore, the necessary of water content increased gradually as the percentage of eggshell increased.

Table 5: Normal Consistency Test & Setting Time- CYLINDER-2.5 (%)

Contents	Time (Clock)	Time (Minutes)	Penetration (mm)	Remarks
Materials: Eggshell Quantity: 2.5% out of 500gm Water: 31% Consistency: 9 Start time: 12:10pm	12:40	30	Full-40	
	12:55	45	Full-40	
	1:05	55	39	
	1:15	65	38	
	1:25	75	37	
	1:30	80	36	
	1:35	85	35	
	1:40	90	34	
	1:45	95	33	
	1:50	100	32	
	1:55	105	30	Initial Setting Time
	2:00	110	28	
	2:05	115	26	

	2:10	120	24	
	10:40	600	00	Final Setting Time

Table 6: Normal Consistency Test & Setting Time- CYLINDER-5 (%)

Contents	Time (Clock)	Time (Minutes)	Penetration (mm)	Remarks
Materials: Eggshell Quantity: 5% out of 500 gm Water: 35% Consistency: 7 Start time: 12:05pm	12:35	30	Full-40	
	12:50	45	Full-40	
	1:05	60	38	
	1:10	65	35	
	1:15	70	33	Initial Setting Time
	1:20	75	23	
	1:25	80	18	
	10:35	600	00	Final Setting Time

Table 7: Normal Consistency Test & Setting Time- CYLINDER-10 (%)

Contents	Time (Clock)	Time (Minutes)	Penetration (mm)	Remarks
Materials: Eggshell Quantity: 10% out of 500gm Water: 40% Consistency: 10 Start time: 11:50am	12:20	30	Full-40	
	12:30	40	Full-40	
	12:40	50	39	
	12:50	60	38	
	1:00	70	37	
	1:10	80	35	
	1:20	90	30	Initial Setting Time
	1:30	100	29	
	1:35	105	23	
	1:40	110	20	
	1:45	115	18	
	10:20	600	00	Final Setting Time

For 2.5% eggshell powder, the initials and end of setting times were about 1 hour 55 minutes and approximately 10 hours 40 minutes, respectively; normal consistency was at least with a water requirement of at least 31%. With 5% eggshell replacement, initial and final setting time were 1 hr 20 mins and 10 hrs 35 min with the water demand going up to 35%. At the 10% of eggshell, initial and final setting times were 1 hr 20 min and 10 hrs 20 min and optimum water at approximately 40%.

Table 8: Waste (Eggshell) reduction

Egg consumes per capita per year [19]	Total Population in BD (crore)	Total egg consumes (crore)	Weight of an eggshell (gm)	Total weight of Eggshell (gm)	Total weight of Eggshell (Tons)
136	17	2312	5	$11.56X10^{10}$	115600

Table 9: Total save due to use of Eggshell Per Year

Total weight of Eggshell (Tons)	Save Cement (Tons)	Cement Price per tons (TK)	Total saves (Taka)
115600	115600	10,000	115,60,00000

The Table 8 and Table 9 presented demonstrate the potential economic and environmental benefits of utilizing eggshell waste in Bangladesh. With an estimated 136 eggs consumed per capita annually and a total population of 170 million, the country generates approximately 115,600 tons of eggshells each year. These eggshells, weighing about 5 grams per shell, contribute to significant waste, which, if repurposed, could have substantial economic value. The second table illustrates that the use of this eggshell waste could potentially replace 115,600 tons of cement, saving up to 1.156 billion taka in cement costs. This suggests that eggshell recycling could not only help reduce the environmental impact by lowering the demand for raw materials in cement production but also lead to considerable economic savings. This approach offers both a sustainable waste management solution and a cost-effective alternative to traditional construction materials, which could benefit various industries in Bangladesh.

3.3 Discussion

The experimental results lead to several significant conclusions with regard to the replacement of a part of the cement by eggshell powder.

Compressive Strength Decrease: Generally, if eggshell powder is substituted to the cement, the compressive strength of concrete tends to be lower than that of reference concrete (ES 0%). This reduction is attributed to the increased voids in the mix and lower binding potential of eggshell powder as opposed to Portland cement.

Level of replacement: Performance and durability are reasonably satisfactory at moderate level of replacement (2.5–5%). It is after 10% replacement that the loss of strength becomes evident.

Water Requirement and Workability: The increase in eggshell content increased the water requirement for constant workability as observed in standard consistency tests. This must be taken into account in the concrete mix design to avoid problems of workability.

Lightweight Concrete: By lowering the concrete's overall density, eggshell powder replacement makes it appropriate for uses like paving blocks, benches and temporary structures that call for lightweight materials.

Environmental Impact: When eggshells are added to cement, it puts waste in a value-added position and reduces the environmental effect of cement production. It is observed from Tables 2-4 and Figures 5 that it is correlated between the content of eggshell and properties of concrete. It may have some loss in strength, but there are interesting applications for temporary of non-bearing components of concrete.

This study highlights the economic and environmental benefits of recycling eggshell waste in Bangladesh. With an annual consumption of 136 eggs per capita and a population of 170 million, approximately 115,600 tons of eggshells are generated in Bangladesh. If repurposed, these eggshells could replace an equivalent amount of cement, saving up to 1.156 billion taka. This not only reduces environmental impact by lowering the demand for raw materials but also offers significant cost savings, presenting eggshell recycling as a sustainable and cost-effective solution for various industries in Bangladesh.

Finally, a small portion of the eggshell powder can be directly substituted for cement. Optimal replacement level that balances between strength, workability and eco-friendly aspect is observed between 2.5% to 5%. Over-replacement (>10%) causes a substantial decrease in the compressive strength resulting from voiding and reduced binding capacity.

4. Conclusion

The applicability of eggshell powder as a cement replacement for concrete production was investigated. The findings indicated that with an increase in eggshell percentage, a lower compressive strength was obtained in the concrete at the different curing periods, while the control mix (0% eggshell powder) showed the greatest compressive strength levels at 7, 14, 21, and 28 days of curing as well as the mixes with additions of 10% eggshell powder had been clearly associated with a significant decrease in strength. Although the findings indicate that the reduction of compressive strength is slightly down with the substitution of 2.5% and 5% eggshell powder, which can be used in low-strength applications such as paving blocks and non-structural members. In addition, the use of eggshell powder also helped to reduce the construction cost as well as the mitigation of the environmental cost of cement production from clogging up landfills as waste. In addition, eggshell-modified concrete is good to use for lightweight-purpose applications. Nevertheless, excessive replacement (> 10%) was found to cause appreciable strength reduction, which could restrict its application in structural concerns. This study also explored the economic and environmental benefits in Bangladesh of using eggshell powder, showing that it could reduce construction costs by saving up to 1.156 billion taka in cement expenses, while also reducing the environmental impact by recycling 115,600 tons of eggshell waste. The results imply that eggshell powder could be a potential partial replacement for cement in concrete application, especially non-structural applications, and additional research may refine its use on a larger scale construction.

Acknowledgment

The authors are thankful to the Department of Civil Engineering, Faculty of Science and Engineering, European University of Bangladesh for providing Laboratory facilities to conduct this study.

Declaration of generative AI use

The authors are solely responsible for all experimental data, analysis, interpretations and conclusions stated in this paper. The authors utilized AI for language polishing, grammar enhancement only. The AI system did not assist with analysis, interpretation or *generation* of scientific content. All the intellectual content, conclusions and findings are those of the authors.

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