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Experimental and Analytical Study of Silica Particles on Self-Healing Concrete

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Abstract

This study aims to investigate the properties of green concrete made with ground granulated blast-furnace slag (GGBS), Robo sand (RS), and coconut shell (CS). GGBS is the mineral admixture used to replace cement. Nano-silica particles (NSPs) and CS are used as coarse aggregates, and RS is the fine aggregate used to replace river sand. The workability, mechanical properties, and durability properties of green concrete are investigated and compared with those of conventional concrete (CC). Test results show that the cement replaced with 30% GGBS and 3% NSPs exhibits superior strength. The compressive and splitting tensile strengths are increased by 24.03% and 42.32% after 28 days of curing, respectively. The workability is improved by 12.22% (slump) and 13.25% (compaction factor) after 28 days of curing. The sorptivity of HM_3 (3.26%) is lower than that of CC due to the uniform distribution between particles. Microstructure evolution is carried out to identify concrete mix behavior.

Keywords: GGBS, nano-silica, coconut shell, Robo sand, durability properties

1. Introduction

Concrete is an artificial matrix with water, cement, fine aggregates (FAs), and coarse aggregates (CAs). Nowadays, the manufacturing of concrete encounters challenges because of the less accessibility of cement, FAs, and CAs in the construction field. Many cement-based self-healing materials are utilized to replace the common ingredients in conventional concrete (CC) to minimize cracking and shrinkage in concrete. Hence, researchers have developed alternatives for FAs, CAs, and cement [1]. However, those developed alternatives may result in environmental pollution. To avoid the pollution, many researchers have focused on developing new alternatives with renewable resources such as organic by-products and waste products for the construction industry. Eco-friendly materials such as agro-based materials are used. Also, with recycling processes, solid waste materials are used as an alternative to aggregates and cement in the construction field, which benefits the environment and human beings at the same time.

Mathew et al. [2] studied the change in concrete properties after replacing cement with coconut shell (CS) ash. The embodied carbon, workability, and mechanical properties of concrete were tested. They found higher strength in the case of 10% replacement and a 15% reduction in embedded carbon in the case of 20% replacement, as compared to the control mix. Palanisamy et al. [3] utilized the CS powder to partially replace FAs and examined the performance of physical and mechanical properties. Finally, from the outcomes of compressive and flexural tests, they concluded that the use of CS decreases density and increases compressive and flexural strengths. With 30% replacement of FAs, the cost of concrete was reduced, as compared with the control mix.

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Ikponmwosa et al. [4] used the rice husk ash (RHA) with the CS ash to replace 30% cement, and found that this combination gave better results than simply using CC. The presence of waste particles increases the strength and reduces the cost of the material. The strength development rate of normal concrete is also found during the first 14 days of curing. Azunna et al. [5] studied the difference between the CC pipes and the concrete pipes made with CS. From three-edge test results, they found that both pipes are within permissible limits as per Indian standard (IS) codes. They concluded that the use of CS should be encouraged in concrete construction. Overall, the prior studies highlighted the need to use admixtures to enhance the features of concrete. They also tried to replace ingredients of concrete with waste materials.

The current research aims to assess the mechanical and durability properties of green concrete made with the combination of ground granulated blast-furnace slag (GGBS), Robo sand (RS), and CS. The contribution of this study includes the following.

(1) This study investigates the effect of GGBS, nano-silica particles (NSPs), and CS on concrete by analyzing the fresh properties, mechanical properties, and durability properties of various designated mixes.

(2) This study compares the experimental results of various designated mixes with CC to identify the optimum mix.

2. Methodology

Green concrete specimens are cast and cured after being synthesized with various compositions, i.e., Mix – I, Mix – II, Mix – III, Mix – IV, and Mix – V. The workability, mechanical properties, and durability properties of the specimens are tested. The effect of the addition of dispersive particles is identified using surface morphology analysis. The entire process is shown in Fig. 1.

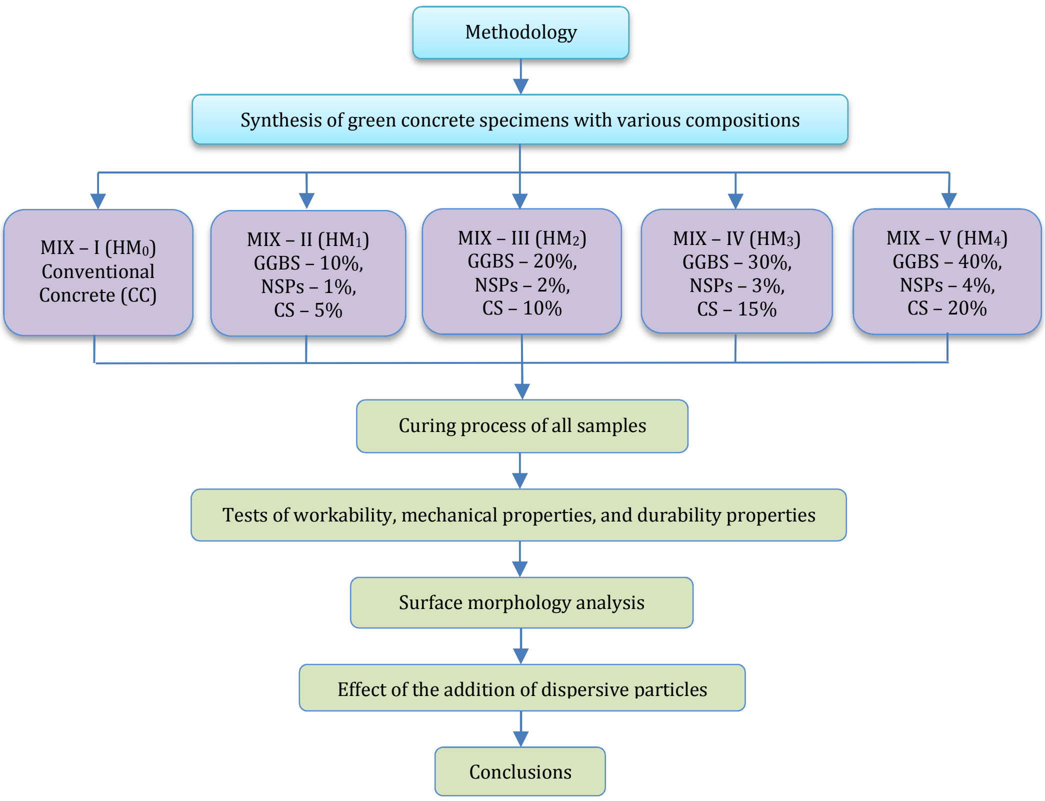

Fig. 1 Methodology of this study

2.1. *Materials*

The elements adopted in this research are cement, FAs (natural river sand and RS), CAs, GGBS, CS, NSPs, and potable water. The following section contains information about the materials utilized. Fig. 2 shows the raw materials of GGBS, CS, and nano-silica powder.

(a) GGBS (b) Coconut shell (c) Nano-silica powder

Fig. 2 Raw materials for the preparation of concrete

2.1.1. Cement

Cement is a binding material in concrete. In this project, the OPC 53 UltraTech brand is used. Tests according to IS 12269-2013 for cement are conducted and found suitable [6]. The chemical and physical characteristics of cement are placed in Tables 1 and 2.

Table 1 Chemical properties of cement

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O	K_2O	LOI
Composition (%)	21.36	4.16	4.32	60.58	3.26	1.70	0.28	0.36	2.18

Table 2 Physical properties of cement

Test particulars	Results obtained
Fineness	6.3%
Initial and final setting time (minutes)	35 & 410 mins
Specific gravity	3.09
Normal consistency (%)	31%
Compressive strength (N/mm^2)	51

2.1.2. Fine aggregate (FA)

Natural river sand is the FA used to cast CC. The crushed stone aggregate (RS), which passes through a 0.075 mm sieve and retains the size of 4.75 mm, is considered the alternative for natural river sand. RS is clean and free from contaminants. The RS used in this study is obtained from Silica Mines & Minerals, Bangalore, India. Tests according to IS 2386.1-1963 are carried out and found suitable [7].

2.1.3. Coarse aggregate (CA)

A local granite crushed stone (with the size of 20 mm) is used as a CA and is obtained from Sri Srinivas Granites, Tirupati, India. It assembles solid and hard stacks of concrete with cement and sand, and supplies mass to concrete. Tests according to IS 2386.1-1963 are conducted and found suitable [8].

2.1.4. Ground granulated blast-furnace slag (GGBS)

GGBS is obtained when making iron in blast furnaces. It has cementitious properties and is obtained from Astrra Chemicals, Chennai, India. The chemical and physical characteristics of GGBS are represented in Tables 3 and 4, as shown below.

Table 3 Chemical properties of GGBS

Elements	SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	Na_2O	LOI
Composition (%)	27-38	7-15	0.2-1.6	0.15-0.76	34-43	0.2-0.48	Bal

Table 4 Physical properties of GGBS

Test particulars	Results obtained
Specific gravity	2.88
Surface area (g/cm^2)	1200
Bulk density (Kg/m^3)	1195
Optimum moisture content (%)	32

2.1.5. Nano-silica particles (NSPs)

The NSPs in the cementing process can accelerate the early hydration of concrete, which is beneficial for strengthening the early strength of concrete. The NSPs used in this study are obtained from Astrra Chemicals, Chennai, India. The chemical and physical properties of NSPs are represented in Tables 5 and 6.

Table 5 Chemical properties of NSPs

Elements	SiO_2	Na_2O	Al_2O_3	SO_3	Fe	Ca	Cu	LOI
Composition (%)	99.4	0.45	0.075	0.05	0.25	0.12	0.16	Bal

Table 6 Physical properties of NSPs

Test particulars	Values
Density	2.17-2.66 gr/cm^3
Melting point	±1700°C
Boiling point	2300°C
Color	White
Bulk density	0.011 gr/ml

2.1.6. Coconut shell (CS)

CS is an agricultural by-product widely used in India. It is beneficial for strengthening concrete and is obtained from SRP Global Exports, Chennai, India. The CS's chemical and physical properties are represented in Tables 7 and 8 as shown below.

Table 7 Chemical properties of CS

Element	Cellulose	Hemi celluloses	Lignin	Pectin	Moisture content	Microfibrillar angle (degree)
wt.%	32-43	0.15-0.25	40-45	3-4	8	30-49

Table 8 Physical properties of CS

Test particulars	Results obtained
Specific gravity	1.33
Bulk density (Kg/m^3)	800
Shell thickness (mm)	3.09
Water absorption capacity (%)	15.17
Fine modulus	3.19

2.2. Preparation of coconut shell into ash

The CS waste is the agro-waste producing 12.3 million tons of coconuts annually in India. The CS used in this study is collected from a local resource, Tirupati, India. The CS ash is suitable for making carbon black due to its excellent natural structure and low ash quantity. Initially, CS is thoroughly cleaned with distilled water and dried at room temperature for 24 hrs. Later, it is transferred into a tubular furnace and heated at a temperature of 550°C. The CS ash is sieved through 200 sieves.

2.3. Mix design

The design M30 mix is carried out for CC as per IS 10262-2019 [9], and the same design mix is used to prepare the concrete by replacing its ingredients with GGBS, NSPs, RS, and CS. The hybrid mix (HM) ratios of M30 grade concrete for a cubic meter are listed in Table 9.

Table 9 Mixed proportion of biohybrid blended concrete mixture

Serial no.	Designation	Cement (%)	River sand (FA) (%)	CA (%)	Replacement (%)			
					GGBS	NSPs	RS	CS
1	HM_0	100	100	100	0	0	0	0
2	HM_1	89	0	95	10	1	100	5
3	HM_2	78	0	90	20	2	100	10
4	HM_3	67	0	85	30	3	100	15
5	HM_4	56	0	80	40	4	100	20

3. Tests

The compressive strength of concrete with different mixes is tested using a universal testing machine (UTM), and the test results are depicted as a pictorial diagram. The specimens are prepared by mixing and filling the concrete in the molds with a suitable layer of 50 mm and compacting the concrete in a cube (150 × 150 × 150 mm) [10]. The splitting tensile samples are prepared by mixing and filling the concrete in the specimens with a suitable layer of 50 mm and compacting the concrete in a cylinder with a length of 300 mm and a diameter of 150 mm using UTM. The samples of the cylinders are tested and cured for 7, 14, 21, and 28 days. Tests according to IS 5816-1999 are carried out [11].

Various tests are conducted on the specific gravity of cement, and the dry sieving method is conducted to test the consistency of cement, fineness of cement, soundness, as well as initial and final setting times. Similarly, several tests are conducted on GGBS to determine the specific gravity, strength, initial setting time, and fineness. In this study, the tests conducted on aggregates are sieve analysis, specific gravity, bulking of sand, and water absorption tests. The preparation and testing samples are shown in Fig. 3 and Fig. 4.

After preparing the mix with various proportions, the workability tests are conducted on fresh concrete, and the mechanical tests are conducted on hardened concrete. The compressive, splitting tensile, and flexural strength tests are performed on the specimens (cube, cylinder, and beam).

(a) Accelerated chamber (b) Concrete mixing (c) Preparation of samples

Fig. 3 Mixing and sample preparation

(a) Compression test (b) Tensile test (c) Slump test

Fig. 4 Testing apparatus

4. Results and Discussion

4.1. Workability of concrete

The slump cone and compaction factor tests on green concrete are shown in Table 10. The slump cone test is conducted according to IS 1199-1959 [12]. In the compacting factor test, an apparatus with two upper and lower hoppers and a cylinder is placed one by one according to the procedure. The test is carried out according to IS 1199-1959 [13]. The composition factor is calculated by using Eq. (1).

$$Compaction\ factor = \frac{w_1 - w_2}{w_2 - w} \tag{1}$$

where w is the empty cylinder weight, w_1 is the weight of the cylinder and free fall concrete, and w_2 is the weight of the cylinder and hand compacted concrete.

With the combination of 30% GGBS, 3% NSPs, and 15% CS, the workability is increased, and the slump flow is later decreased. The sulphonated naphthalene-based superplasticizers are mixed in the concrete at a dose of 1.5% of the cement weight to improve the workability. It is found that, in the case of hard particles (HM_3), the slump increases from 90 to 101 mm (12.22%) and the compaction factor increases from 0.83 to 0.94 (13.25%), compared to the case of CC. Hence, HM_3 is considered the optimum mix for better performance. Amin et al. [14] concluded that using 15% of CS and NSPs in concrete would cause the decrease in slump and the delay in initial and final setting time. The slump slightly increases to 95 (HM_4) because the high mix does not dissolve in concrete. Hence, the addition of NSPs and CS is a significant effect illustrating good workability, reduced heat of hydration, and cost reduction in concrete production.

Table 10 Workability of HM

Hybrid mix ID	Slump (mm)	Compaction factor
HM_0	90	0.83
HM_1	92	0.87
HM_2	97	0.91
HM_3	101	0.94
HM_4	95	0.89

4.2. Mechanical studies

4.2.1. Compressive strength

Compressive strength values are attained by examining cubes made with CC and different HMs, as shown in Fig. 5. All the mixes contain a strength above 30 MPa, which is the anticipated strength. All the mixes show an increase in compressive strength at the 28th day of curing. The compressive strength improves with the use of CS and GGBS with NSPs, later decreasing at a certain level, as shown in Fig. 5.

In the case of using 15% CS and 30% GGBS with 3% NSPs (HM_3), it is found that the compressive strength increases after 7 days from 20.67 to 24.17 N/mm^2 (16.93%), after 14 days from 26.72 to 30.68 N/mm^2 (14.82%), after 21 days from 33.68 to 39.34 N/mm^2 (16.81%), and after 28 days from 36.75 to 45.58 N/mm^2 (24.03%), as compared to the case of CC. Hence, the HM_3 is considered the optimum mix for better performance, tends to fill the pores, and increases the compressive strength of concrete. According to Gao et al. [15], substituting 25% of the CC with a nano combination resulted in more than 45 N/mm^2 after 28 days. Furthermore, filler components enhanced the compressive strengths of CC combinations at an early age. Test results show that the GGBS with NSPs and CS shows superior mechanical properties. The compressive strength is reduced in the case of HM_4 due to the balling effect of hybrid content.

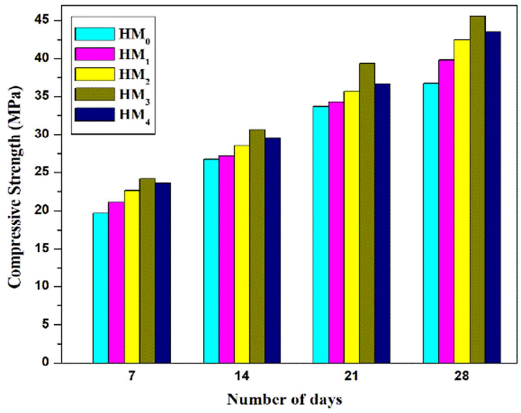

Fig. 5 Compressive strength of various mixes

4.2.2. Splitting tensile strength

The tensile strength of mixes is attained by performing a split tensile test on standard cylindrical specimens. Incorporating HMs into CC raises the strength by 32% after 28 days curing, as shown in Fig. 6. The splitting tensile strength increases with the use of 3% NSPs and 15% CS. In the case of GGBS with 3% NSPs (HM_3), it is found that the splitting tensile strength increases after 7 days from 3.05 to 4.23 N/mm^2 (38.69%), after 14 days from 4.08 to 5.73 N/mm^2 (40.44%), after 21 days from 4.51 to 6.37 N/mm^2 (41.24%), and after 28 days from 4.75 to 6.76 N/mm^2 (42.32%), compared to the case of CC.

Hence, HM_3 is considered the optimum mix for better performance. The hydration of CC enhances the mechanical properties of samples at later ages by decreasing macro cracking size and increasing CS/NSPs ratio. Nandhini et al. [16] conducted cracking control of traditional concrete and CC modified with NSPs and FAs. They suggested that the amount of paste in the mix be increased in strength so that fragments can be dispersed more evenly, ensuring a high level of workability. The reduction in tensile strength observed in the case of HM_4 is attributed to an increase in porosity and distribution of pores. Therefore, the presence of NSPs and CS tends to fill the pores and control the crack growth, increasing the mechanical strength of concrete.

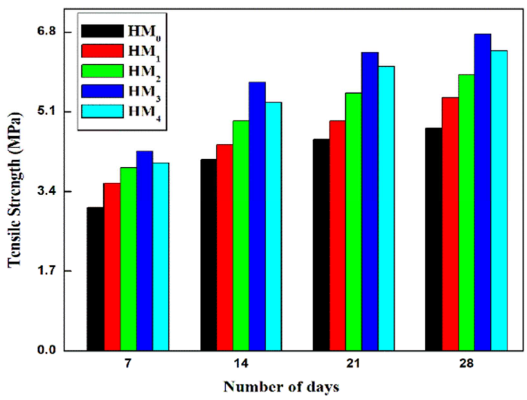

Fig. 6 Splitting tensile strength of various mixes

4.3. Durability studies

4.3.1. Permeable void test

The permeable voids are determined as per ASTM C 642-82 on cured samples with cubes (150 × 150 × 150 mm) [17]. The surface of the cubes is cleaned with a dry cloth, and the weights of the saturated surface dry cubes are noted. These cubes are kept in a hot oven at 105°C for a long time to ensure a consistent weight. Constant weight is reached after the oven-dried cubes are soaked in water, and an increase in weight is found at frequent periods. The percentage of permeable spaces of the specimens is calculated using Eq. (2).

$$Percentage\ of\ permeable\ voids\ (\%) = \frac{A-B}{V} \times 100 \quad (2)$$

Here, A is the mass of the surface-dried saturated specimen, B is the mass of the oven-dried sample, and V is the volume of the samples.

The ASTM C 642 [18] classifies the volume of permeable voids (VPV) into categories: the VPV less than 14% represents the excellent quality of concrete, the 14-16% VPV is good, the 17-19% VPV is marginal, and the 19% VPV represents poor quality of concrete. The results of penetrable voids for CC and HM are exhibited in Table 11. It is identified that a lower VPV is found (11.21%) in the case of HM_3 compared to the normal mix. This may be attributed to calcium-silicate hydrate (CSH) gel filling up the cracks and pits present in concrete and improving material stability. High compressive strength cubes that are less porous will improve the permeable void ratio. The strength of the concrete is enhanced with the respective usage of NSPs and CS in normal concrete. Further addition of HM_4 shows increasing permeable voids (12.68%). It may appear due to the higher paste content and dosage of superplasticizer adopted for producing CC. This leads to an increase in porosity suggested by Chen et al. [19].

Table 11 Permeable void test

Mix ID	Surface saturated specimens (kg)	Oven-dried specimens (kg)	Permeable voids (%)
HM_0	7.95	7.44	15.07
HM_1	8.2	7.71	14.53
HM_2	8.04	7.64	13.96
HM_3	7.96	7.49	11.21
HM_4	7.99	7.52	12.68

4.3.2. Sorptivity test

In unsaturated specimens, sorptivity is an indication of moisture activity. Here, it is identified as a vital measure for assessing the long-term durability of concrete. As a result, the testing method used for its resolution is a good indicator of the quality of close-to-surface concrete. It resembles the way that water and other corrosive agents will pass through many concretes [20].

A concrete sorptivity coefficient is critical for estimating the framework's mortality rate and improving its performance. Measuring the capillary rise absorption rate on a uniform product can determine the sorptivity. It is dried in an oven at 105°C. It is kept in water at a depth of 5 mm from the bottom of the sample, and the flow from the outside of the sample is restricted through non-absorbent covering. Later, the weight of the specimen is used to measure the amount of water absorbed for a few minutes. Within 30 seconds of each procedure, wet cells are used to wipe away any surface water accumulated. Permeable materials can absorb and transmit water through the capillary action, referred to as the sorptivity coefficient (K). The average time denominator increases the total collective water absorption (at each inflow surface location) (t).

The sorptivity values are explored for CC and HMs, as presented in Table 12. Table 12 shows that the sorptivity of HM_2 (5.08%), HM_3 (3.26%), and HM_4 (4.21%) is lower than that of CC due to uniform distribution between particles. Praveenkumar and Vijayalakshmi [21] confirmed that 20% of GGBS with NSPs samples showed an 8% reduction in sorptivity after 150 days. Hence, it is attributed to the effect of these pozzolans and the decrease in permeability.

Table 12 Sorptivity test

Serial no.	Designation	Sorptivity (%)		
		90 days	120 days	150 days
1	HM_0	7.26	7.19	7.04
2	HM_1	6.82	6.36	6.22
3	HM_2	5.45	5.21	5.08
4	HM_3	3.76	3.47	3.26

5. Conclusions

The usage of waste materials for raw materials is beneficial to the environment and minimizes material costs. Based on the experiment in this study, it is found that the combination of using GGBS and NSPs to replace 33% cement, using RS to replace 100% river sand, and using CS (HM_3) to replace 15% CAs is the optimum combination to be the alternative for CC. The following conclusions are drawn.

(1) In the case of hard particles (HM_3), the slump increases from 90 to 101 (12.22%), and the compaction factor increases from 0.83 to 0.94 (13.25%), compared to the case of CC. It is because of the addition of the superplasticizer in the HM.

(2) The compressive strength of CC is 45.58 N/mm^2 after 28 days of curing, while the addition of CS and GGBS with NSPs is used as a binary blended concrete resulting in increased strength for all grades. With the optimum mix (HM_3) of 15% CS with 3% NSPs for cement replacement, the strength obtained is 24.03% higher than with CC.

(3) The tensile strength achieved is 6.76 N/mm^2 in the case of the HM_3 mix after 28 days, which is 42.32% higher than in the case of CC due to the uniform distribution between particles and high hardness. Further addition of HM_4 to blended concrete reduces the mechanical strength due to the increasing porosity level and distribution of pores.

(4) The VPV in concrete is 11.21% (less than 14%, excellent) in the case of HM_3, which is better than in the case of CC.

(5) Among all the mixes, HM_3 shows the maximum reduction (3.26%) of sorptivity value after 150 days. From the rapid chloride permeability test (RCPT), the resistance to chloride ion penetration in the case of HM_3 is 32% higher than CC after 150 days.

(6) The results show that it is suitable to use GGBS (with NSPs), RS, and CS to replace cement, river sand, and CAs in the concrete, respectively. HM_3 is considered the optimum mix for better performance, tends to fill the pores, and increases the mechanical strength of concrete. Adding reinforcement particles will delay beams' damage and improve their durability.

Conflicts of Interest

The authors declare no conflicts of interest.

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