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Research Article

An analysis of the effectiveness of new generation self-leveling lightweight composite screed for underfloor heating systems

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ABSTRACT

Energy saving has become a significant concern in recent years due to increasing carbon emissions and environmental pollution. When examined from a global perspective, it is known that the energy consumed for heating and cooling of buildings is relatively high. In this regard, researchers attach great importance to energy efficiency issues. In recent years, an issue that has been given priority in heating buildings more efficiently is underfloor heating systems. Underfloor heating systems are composite structures of slab concrete, insulation material, hot water pipes, and screed. Here, the thermal performance of the screed is vital as the hot water pipes remain embedded in the screed. This study has produced a new composite and self-leveling screed type that can transfer heat easily. For this purpose, nine screed mixtures were prepared, including a reference (nearly conventional) screed mortar. The screed mortars' flowability, density, and compressive strength were determined regarding physical properties. Thermal properties, thermal conductivity, specific heat, thermal diffusivity, and heat storage analyses were carried out. In the second stage of the study, a basic underfloor heating system was installed, and the temperatures of the water circulating in the system, the outer surface of the pipe carrying the water, and the outer surface of the screed were measured at specific periods. According to the study results, it has been observed that depending on the thermal properties of the screeds produced within the scope of this study, when used in underfloor heating systems, it can transfer heat from the hot water pipes to the surface with minimum losses.

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1. INTRODUCTION

Self-leveling leveling screed is a cement-based polymer-modified, self-leveling mortar with high fluidity to obtain generally a smooth floor surface. The first pumpable self-leveling flooring material was developed in the mid-1970s. This product uses Portland cement as a binder with a casein-based flowing agent to provide an easy and quick way to level concrete floors before applying a topcoat [1].

Self-leveling screed has a composite structure consisting of binders, fillers, polymers, and additives. Screed mortar

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can be named under separate definitions according to the type of binder material. These nomenclatures are grouped into five different categories in the TS EN 13813 standard [2]: cementitious screeds (CT), calcium sulfate screeds (CA), magnesite screeds (MA), mastic asphalt screeds (AS) and synthetic resin screeds (SR). It is seen that finely ground mineral materials such as sand and limestone are mainly used as filling materials. Alternative mineral and chemical polymer-based additives of different origins can be used as additives, for example, to control setting time, curing time, flow properties, air entrainment, etc. [3–5].

Self-leveling screed mortar generally has three primary uses. The first is underlays, which smooth any surface and remove irregularities that the concrete may have [6]. This application is done before the installation of all kinds of floors. For example, it can be used to level the floor under materials such as Polyvinyl Chloride (PVC), tiles, ceramics, granite ceramics, marble, natural granite, parquet, carpet, laminated flooring, laminate flooring, rubber flooring. The second place of use is to apply self-leveling mortar as a finishing coat from the beginning of the project to act as an actual finished floor without the need for a floor covering. A third use of self-leveling mortar is a repair material for damaged concrete in applications such as bridges or roads. In addition, self-leveling mortars can provide a smooth and durable new surface for decorative treatments in areas with heavy traffic, residential, commercial, industrial buildings, hospitals, supermarkets, educational buildings, hotels, and shopping malls. It is also used in [7]. In addition, their use can be seen in applications under epoxy. Self-leveling mortar is a ready-to-use mortar that must be mixed with water before being used directly. It is also used to create a flat and smooth surface with a compressive strength similar to or higher than conventional cement mortar. It is mainly used as a backing or filling material.

It can be seen that there are several types of flooring in actual applications (Figure 1). Among these, underfloor heating systems have become popular in recent years. Today, the need for self-leveling mortar applications has increased due to the flatness and smoothness of floor coverings, especially in underfloor heating systems. These systems have been widely used as an alternative to conventional heating systems in recent years [8]. The main logic of the underfloor heating system is heating the area by giving heat to the pipes (water system) or cables (electric system) placed under the floor from the floor surface to the indoor environment. An underfloor heating system, which expands the surface area, consumes less energy by reducing the temperature difference and provides more comfortable heat distribution. Since most of the energy consumption in buildings originates from the heating and cooling [9], floor heating systems have become an essential application in recent years in terms of energy efficiency used for heating in buildings, especially to comply with strict rules such as European Union Energy Efficient Directive [10]. Underfloor heating systems provide uniform temperature distribution, reduce distribution losses, and increase thermal comfort compared to conventional systems by minimizing the vertical temperature gradient [11–13]. In reinforced concrete structures, underfloor heating systems are applied as slab on the lowest layer, insulation material on a slab, hot water pipes on insulation material, screed on insulation material and pipes, and coating material on the last layer. A more detailed view of underfloor heating systems is given in Figure 2. The underfloor heating system's effectiveness depends on these layers' performance. The most important of these layers can be considered as the screed material since it remains embedded in the hot water pipes. The thermal conductivity of the screed material plays a vital role in the system's efficiency. It should be expected that the screed material used in underfloor heating systems can self-level in a way that minimizes workmanship errors and has an identity that conducts heat as much as possible. An underfloor system with a high thermally conductive self-leveling screed provides improvements over conventional screed or slab construction systems. Increased thermal conductivity reduces reaction time, and the flowing nature of the self-leveling screed results in an improved pipe coating, enhancing the pipe/screed interface, which, combined with homogeneity, can further improve thermal energy transfer. The inherent strength, durability, and low shrink characteristics of screeds enable depths to be reduced without compromising performance.

Wu et al. [14] examined the thermal conductivity of concrete with the addition of graphite. They used graphite with the replacement of fine aggregate in different mass ratios. They found that the thermal conductivity of concrete specimens can increase from 20% to 50%. However, compressive strength was reduced to 90% at a replacement level of 15%. Liu et al. [15] studied the thermal conductivity of carbon fiber-reinforced concrete. They used 0.5, 1, and 1.5% of volume carbon fiber in concrete production. According to

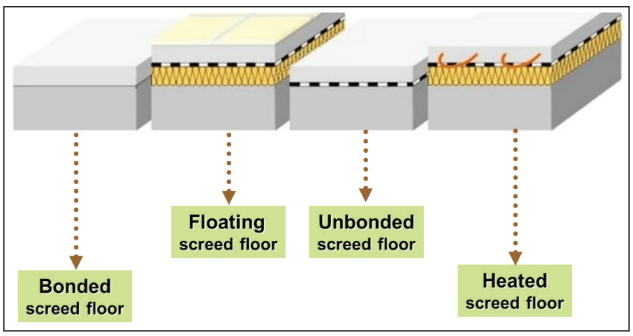

Figure 1. Different Types Of Flooring Applications.

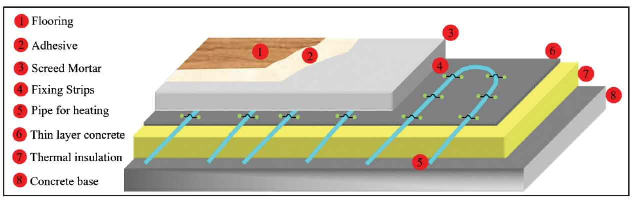

Figure 2. Detailed view of underfloor heating systems.

their test results, they stated that when the water: cement (w/c) ratio is 0.5, the thermal conductivity of carbon fiber reinforced concretes maximum. Besides, they found that increased carbon fiber content increases the thermal conductivity. Although there are few results in the literature that blast furnace slag and silica fume reduce thermal conductivity in concrete Fields[16,17], it has also been determined that these admixtures can increase the thermal conductivity coefficient by reducing the voids by improving hydration [18]. Khan [19] found that higher thermal conductivity in concrete may be obtained using quartz sand compared with basalt, limestone, and siltstone. Although mica is an insulating and high-temperature resistant material with a similar structure to graphite [20], Zhang and Zhang [21] found that the thermal conductivity of plasticized polyvinyl chloride (P-PVC)/mica composites increased with a linear trend with the increase in the mica content. The thermal conductivity of mica in any direction parallel to the cleavage plane was found to be relatively high in previous research (from 3.7 to 4.0 W/mK) and perpendicular to the plane relatively low (from 0.44 to 0.46 W/mK) [22].

When the literature is examined, more research must be done on using self-leveling lightweight composite screed (SLCS) products. In this context, it is necessary to study the applicability of this type of cement-based screed mortars in today's trending and advantageous new underfloor heating systems.

This paper aims to contribute to a better knowledge of the performance of a unique mix design of superplasticizer, mineral admixtures, carbon fiber, quartz sand, mica, and graphite with cement binder for SLCS. An experimental study was conducted to develop cement-based screed mortars with nine different mix designs tested in the laboratory are discussed. In the experimental analysis, especially the effects of an increase in graphite content on the density, compressive strength, thermal conductivity, specific heat, thermal diffusivity, and heat storage capacity of the SLCS mortar were analyzed in detail, and the findings were briefly discussed in this study.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Cement

CEM I 42.5R ordinary Portland cement (PC), similar to ASTM Type I cement, was utilized in the design of nine screed mixes. The specific gravity of the cement is 3.15. It is used as the primary binder material.

2.1.2. Blast Furnace Slag

The blast furnace slag (BFS) used in this study was supplied from commercial establishments in the Izmir-Foça region of Türkiye. The unit weight of the BFS is 1550 ± 50 kg/m^3. The average particle size of BFS is classified as 125 μm. It is used as a mineral admixture in the screed design.

2.1.3. Silica Fume

The maximum particle size of silica fume (SF) is 90 μm. Silica fume was supplied from the Antalya region of Türkiye. The unit weight of the SF is 680 ± 50 kg/m^3. It is used as a mineral admixture in the screed design.

2.1.4. Mica

Mica in powder form is classified as 300 μm in average particle size. Mica powder (MP) was supplied from KALTUN Madencilik A.Ş in the Aydın-Çine region of Türkiye. The unit weight of the MP is 760 ± 30 kg/m^3. It is used as the main filler in the screed design.

2.1.5. Quartz Sand

Quartz sand (QS) is classified in size of 0/1 mm. It was supplied from commercial establishments in the Manisa – Salihli region of Türkiye. The unit weight of the QS is 1450 ± 50 kg/m^3. It is used as the primary aggregate in the screed design.

2.1.6. Graphite

The graphite powder (GP) used in this study was supplied from commercial establishments in the Izmir region of Türkiye. GP is classified as 45 μm in average particle size. The unit weight of the GP is 650 ± 50 kg/m^3. It was used as a conductive material.

2.1.7. Carbon Fiber

Carbon fibers (CF) with 6 mm length were supplied from commercial establishments under market conditions in the Izmir region of Türkiye. The unit weight of the CF is 460 ± 70 kg/m^3. It was used as a conductive material.

2.1.8. Superplasticizer

Polycarboxylate ether (PCE) type superplasticizer (SP) was used to provide self-leveling property to the screed mortars. The SP used in this study was supplied by commercial establishments in the Izmir region of Türkiye.

A general view of all ingredients of SLCSs is shown in Figure 3. Sieve analysis of BFS, QS, and MP is represented in Figure 4.

2.2. Methods

2.2.1. SLCS Production

In this experimental study, different screed mortar mixing ratios were designed to investigate the effect of especially carbon fiber and graphite on self-leveling lightweight composite screeds. In addition, a separate mixture without using CF and GP was designed as a reference screed mixture to accurately examine the effects that may arise from using CF and GP. The design of the composite combinations is given in Table 1.

A mortar was produced close to the conventional cement mortars in terms of mixture ingredients as a reference mortar. In the reference mortar (S0), cement, silica fume, quartz sand, and superplasticizer are used as mixture materials. Mixtures between S1 and S8 are the test mixtures designed

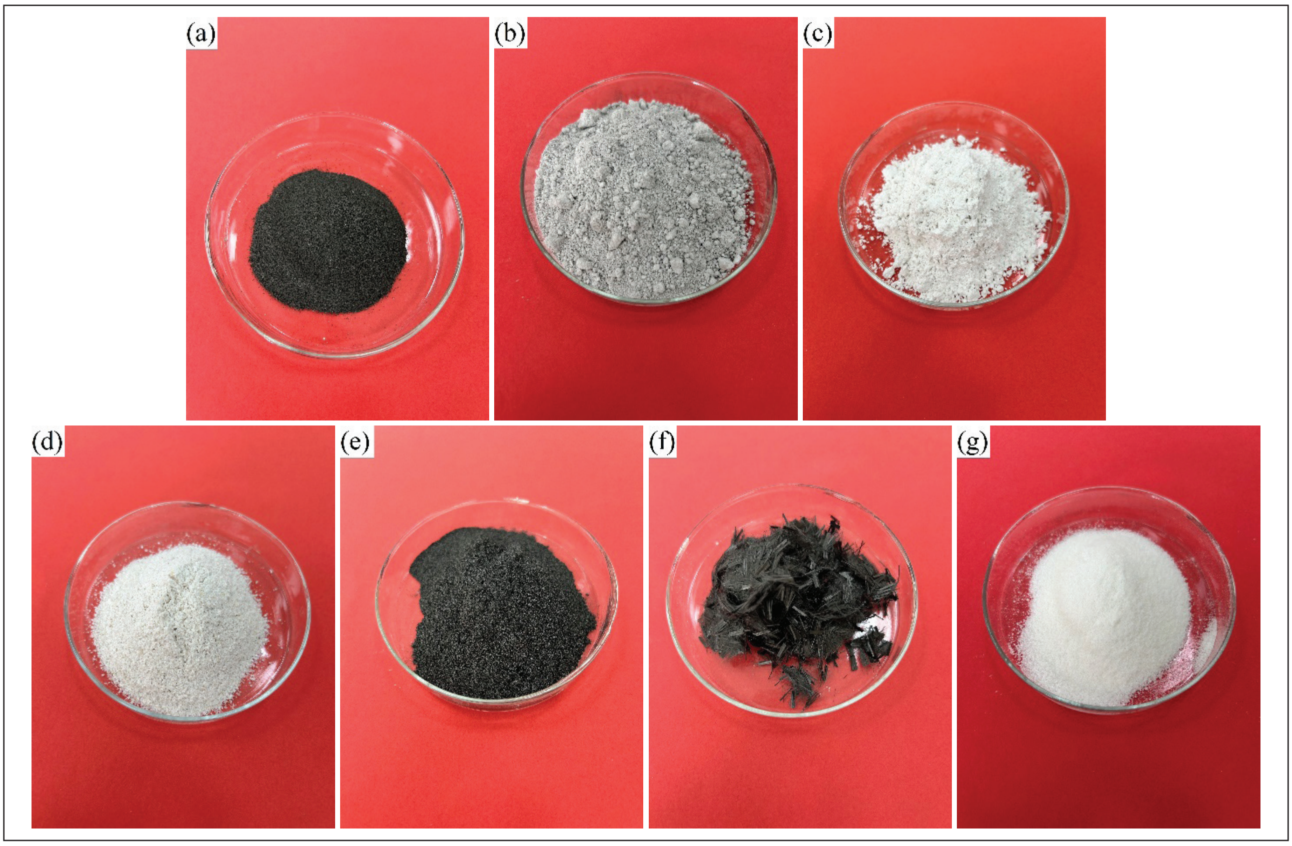

Figure 3. (a) BFS; (b) SF; (c) MP; (d) QS; (e) GP; (f) CF; (g) SP.

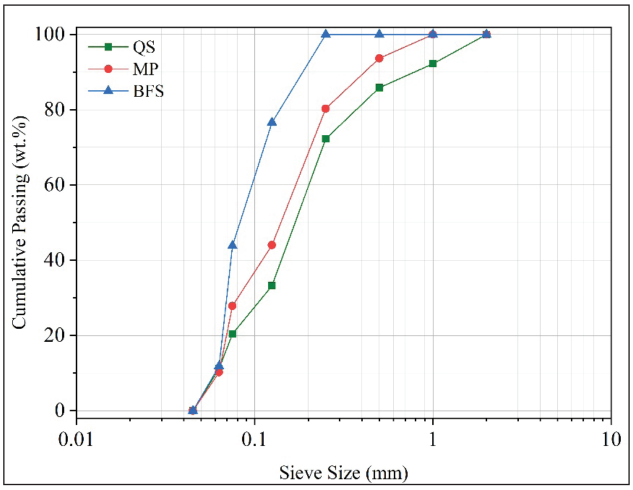

Figure 4. Sieve analysis of BFS, MP, and QS.

to increase the thermal conductivity. In test mixtures, PC (34%), BFS (18%), SF (2.8%), QS (4.9%), CF (0.56%,) and SP (3.22 wt.% of PC) were used in fixed rates. Test mixtures are designed to replace GP and MP with increasing proportions as 0.69, 1.38, 2.07, 2.76, 3.45, 4.14, 4.60 and 5.75 %. In the mixing phase, all solid ingredients were first put in the mixer and mixed for 2 min to achieve a homogeneous dry mixture. Water was added to the mixer to produce fresh cement-based lightweight composite screed mixtures, and the mixture was mixed for another 2 min. The water was regular tap water, and it was at 20 ± 2 °C. The w/c ratio is adjusted according to the constant fresh mortar flow values on the flow table apparatus. Fresh screed mortar samples' flow diameters were determined using the flow table apparatus by ASTM C1437-15 [23]. Flow table test views of S0, S1, S4, and S8 samples are shown in Figure 5. The flow diameters of all samples were produced to be 185 ± 10 mm, w/c ratios were detected, and samples were produced with this principle.

2.2.2. Physical and Mechanical Tests

Fresh and hardened unit weights of mortars were carried out on the fresh and hardened composite specimens concerning TS EN 1015-6 [24] and TS EN 1015-10 [25]. Compressive strength tests were conducted on the hardened composite samples concerning ASTM C109-21 standard [26]. Three pieces of 5×5×5 cm^3 cubic specimens were produced for each series for the compressive strength test. A compressive strength test was carried out on 28 days of the curing period. All test specimens were kept in molds for 24 h at room temperature and removed from molds. After the samples were removed from the molds, plastic sheets were covered on them and cured at room temperature. All tests were completed after the moisture-cured materials were dried in the oven until their weight remained unchanged.

Table 1. Proportions of trial mixtures (% by weight)

Mixture	PC	BFS	SF	MP	QS	GP	CF	SP (wt.% of PC)	w/c
S0	34.0	0.0	2.8	0.00	46.5	0.00	0.00	3.22	0.46
S1	34.0	18.0	2.8	22.31	4.9	0.69	0.56	3.22	0.48
S2	34.0	18.0	2.8	21.62	4.9	1.38	0.56	3.22	0.50
S3	34.0	18.0	2.8	20.93	4.9	2.07	0.56	3.22	0.51
S4	34.0	18.0	2.8	20.24	4.9	2.76	0.56	3.22	0.52
S5	34.0	18.0	2.8	19.55	4.9	3.45	0.56	3.22	0.53
S6	34.0	18.0	2.8	18.86	4.9	4.14	0.56	3.22	0.55
S7	34.0	18.0	2.8	18.40	4.9	4.60	0.56	3.22	0.56
S8	34.0	18.0	2.8	17.25	4.9	5.75	0.56	3.22	0.59

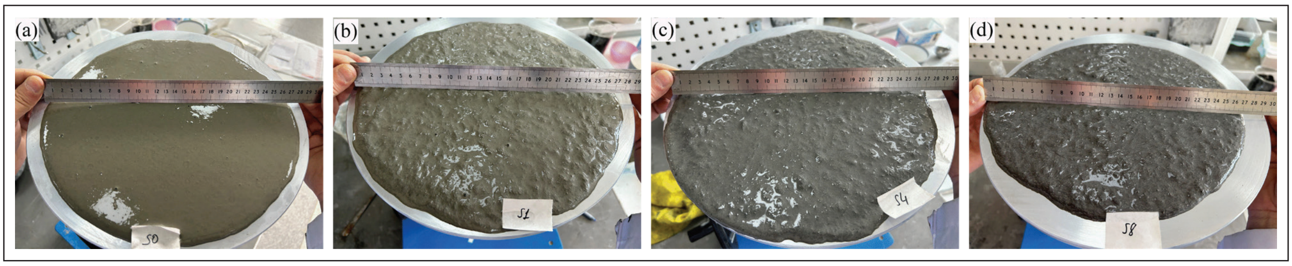

Figure 5. Similar flow diameters of (a) S0; (b) S1; (c) S4; and (d) S8 specimens.

2.2.3. Thermal Properties Tests of SLCSs

For each mixture, three pieces of 20×40×3 cm^3 rectangular specimens were produced to determine the thermal properties of the specimens. Another three 5×5×5 cm^3 cubic samples were produced and used for the test specimens to be cut into pieces to be used in the specific heat value measurements. Again, all thermal property tests were carried out after the moisture-cured materials were dried in the oven until their weight remained unchanged. Thermal conductivity values of test specimens were carried out by hot box apparatus. This laboratory scale hot box device is a device that measures in a steady state via conduction. The Hot Box method allows for measuring thermal conductivity in the test sample, with the option to vary temperature environments between 0 °C and +55 °C. The temperature of each sample surface was measured at a minimum of 9 points, forming a grid on the surface. The thermal conductivity device consists of three components: an electrical heater known as the hot room, the section where the sample is placed, and the cold room. The temperature sensors in the cold and hot chambers were in complete contact with the sample surface, ensuring accurate measurement of the sample surface temperature with a precision of 0.1 °C. The supplied heat could be controlled using a continuously variable current ranging from 20 to 400 watts.

The test device is designed to minimize errors by considering the three-dimensional nature of heat transfer. Before recording temperature data, the sample was allowed to stabilize, and data recording commenced once a steady state was reached. The desired temperature difference between both surfaces of the test sample, positioned within the apparatus, was achieved by applying electrical power (QT, Watt) to the heater. The temperature difference (ΔT, °C) between the surfaces was determined as the average value derived from the measured values. The thermal conductivity value (λ, W/mK) of the test sample was then calculated using the following equation (Eq. 1):

$$\lambda = (Q_T{*}d) / (A{*}\Delta T) \quad (1)$$

Where; λ is the thermal conductivity value of the test sample (W/mK), Q_T is electrical power applied to the heater (Watts), D is sample thickness (m), and A is the heated area in the heating section (m^2). ΔT is the temperature difference between surfaces (°C).

To determine the specific heat value of the hardened SLCS specimens, a calorimeter device and associated formulations with defined technical characteristics in the literature were used throughout the experimental studies [27]. The thermal diffusivity coefficient of the specimens was calculated with Eq. 2.

$$\alpha = \lambda / (\rho{*}C_p) \quad (2)$$

Where; α is thermal diffusivity (m^2/s), λ is thermal conductivity (W/mK), ρ is oven-dry apparent density (kg/m^3), and C_p is specific heat (J/kgK).

The amount of heat stored depends on the specific heat of the medium, the temperature change, and the amount of storage material, which is expressed by Eq. 3 [28].

$$\Delta Q = m \times \int_{T_i}^{T_f} C_p(T).dT \quad (3)$$

Where ΔQ is the heat stored (J), m is the mass of specimen (kg), C_p is specific heat (J/kgK), and dT is the temperature difference.

2.2.4. Basic underfloor heating system production

Screed specimens were produced to be used in underfloor heating systems. Also, a basic underfloor heating experiment setup was prepared to analyze the screed specimens' performance within the study's scope. The symbolic view of the basic underfloor heating system installed is shown in Figure 6. This underfloor heating system installed has an insulation layer at the bottom. Hot water pipes are fixed on this layer. 40 mm thick SLCSs produced in this study were applied to the structure where the hot water pipes were fixed. The temperatures were then measured at three different system points at other times. These are the temperature of the water (T_w), the outside temperature of the pipe carrying the water (T_1), and the temperature of the screed surface (T_2). The experiment was continued for 8 hours. The water was heated in the pipe for the first 4 hours. At the end of this period, the water temperature reaches 45 °C. Afterward, the water heating was stopped, and the water was left to circulate with its temperature and started to cool. During this process, T_w, T_1, and T_2 temperatures were recorded at different times (after 0, 0.2, 0.3, 0.5, 0.6, 0.7, 0.8, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5 and 8 hours).

3. RESULTS AND DISCUSSION

3.1. Physical and Mechanical Tests

The physical and mechanical properties of the screed specimens produced in this study are given in Table 2. Since the fiber and graphite ratios in the mixture change, it is impossible to use a fixed amount of water, so the mixtures are designed with constant consistency. The consistency of the mortars was measured using the flow table, and the water ratio was adjusted so that the flow diameter of the screed mortars was a constant 185 ± 10 mm. It was determined that the fresh and hardened densities of the mortars decreased as the mica ratio decreased and the graphite ratio increased in the mixtures. However, this change is relatively minimal, as shown in Table 2.

On the other hand, the density values of the reference mortar produced with a formula close to the conventional screed mortar are considerably higher than the density

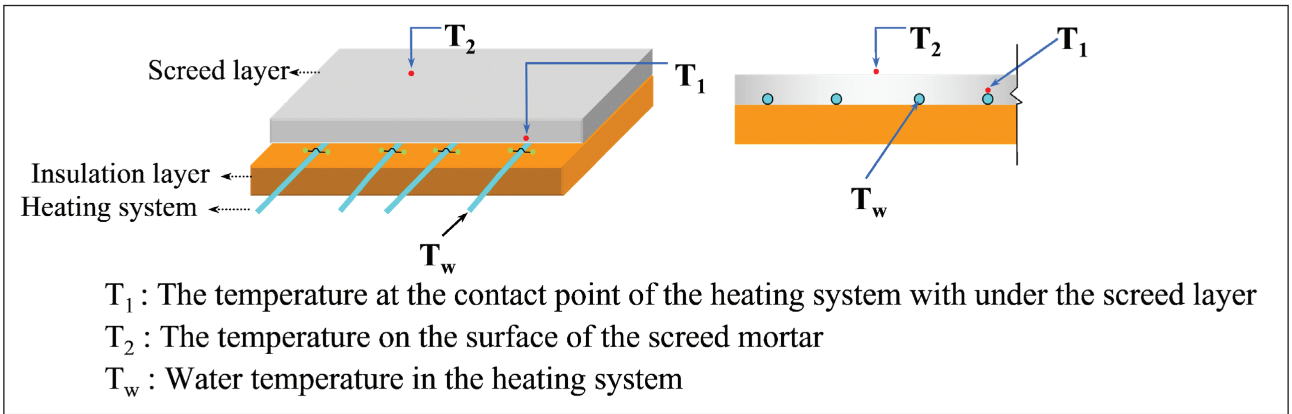

Figure 6. Symbolic view of the measurement locations of the application and temperature values of the screed mortar specimens in the heating system.

Table 2. Physical properties of tested specimens

Mixture	Density in Powder Form (kg/m³)	Fresh Density (kg/m³)	Hardened Density (kg/m³)	Consistency (mm)	Compressive Strength at 28 days (N/mm²)
S0	1198	1773	1585	185±10	18.75
S1	1011	1473	1319	185±10	18.37
S2	1009	1470	1317	185±10	17.63
S3	1008	1468	1315	185±10	17.42
S4	1006	1466	1312	185±10	17.20
S5	1004	1463	1310	185±10	16.66
S6	1003	1461	1308	185±10	16.34
S7	1002	1459	1307	185±10	15.30
S8	999	1455	1303	185±10	14.51

values of the SLCS mortars produced within the scope of this study. Although the hardened densities of the SLCS mortars were almost similar, the increase in the amount of graphite in the mortars caused significant losses in the compressive strength of the mortars (see Figure 7). The significant decrease in compressive strength is due to the lubricating effect of graphite and the weakening of the bond strength in the matrix structure [14]. In this study, the compressive strength of the reference mortar (S0) produced similar to the conventional screed mortar was 18.75 MPa, while the compressive strength of the S8 mortar, which had the highest use of graphite, decreased by 22.61% and was found to be 14.51 MPa. However, higher compressive strength values were obtained than 5 MPa, the lowest screed compressive strength value mentioned in the TS EN 13813 standard [2].

3.2. Thermal Properties Tests of SLCSs

The thermal properties of all specimens are given in Table 3. According to the test results, the thermal conductivity of the reference mixture was 0.597 W/mK, and the thermal conductivity of hardened SLCS specimens using GP was changed between 0.735 and 0.985 W/mK. Generally, thermal conductivity in cement-based materials is associated with the porosity and density of the material [29–31]. Although the density values of the SLCS mortars produced in this study are almost the same, the thermal conductivity values increase depending on the carbon fibers and significantly the increase in graphite in the mortar mixtures (see Figure 8). Compared to the reference screed mortar, the thermal conductivity values of the test specimens increased by 23.12, 26.13, 34.84, 35.68, 42.38, 45.23, 54.77 and 64.99% by MP with GP replacement ratio with 0.69 (S1), 1.38 (S2), 2.07 (S3), 2.76 (S4), 3.45 (S5), 4.14 (S6), 4.6 (S7) and 5.75 % (S8). In other words, the hardened screed mortars get a more conducive form with increased graphite content.

The experimental analysis findings of the specific heat value (Cp) of the SLCS specimens under constant pressure

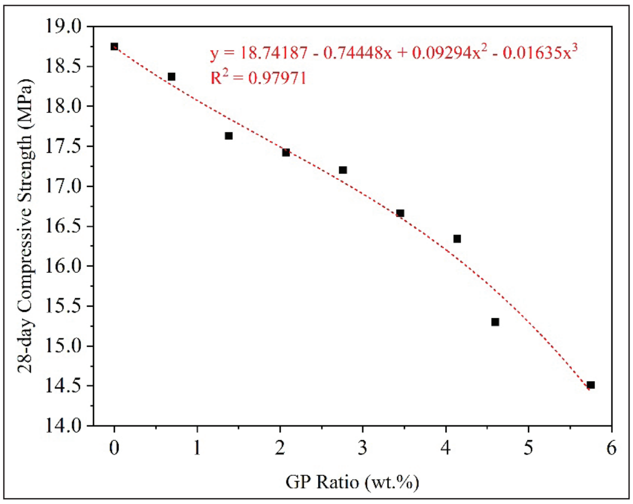

Figure 7. Relation between the GP ratio in SLCS mixtures and compressive strength of SLCSs.

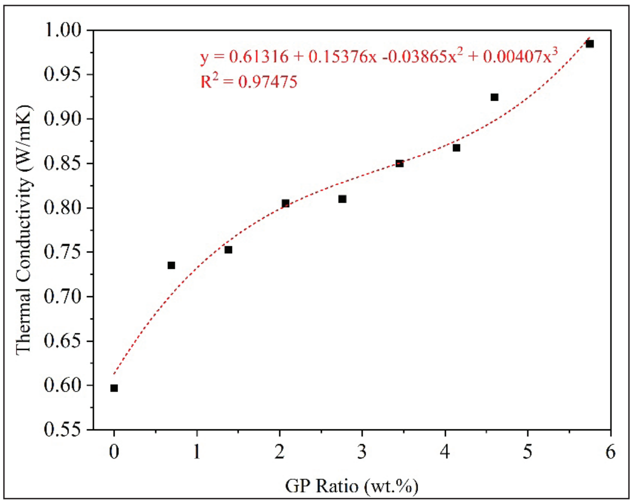

Figure 8. Relation between the GP ratio in SLCS mixtures and thermal conductivity of SLCSs.

Table 3. Thermal properties of tested specimens

Mixture	GP/MP Ratio	Thermal Conductivity (W/mK)	Cp (J/kgK)	Thermal Diffusivity $x10^{-6}$ (m^2/s)	Heat Stored* ΔQ (calories)
S0	0	0.597	1070	0.352	4050
S1	0.03	0.735	1018	0.547	3207
S2	0.06	0.753	974	0.587	3063
S3	0.10	0.805	966	0.634	3033
S4	0.14	0.810	947	0.652	2968
S5	0.18	0.850	918	0.707	2873
S6	0.22	0.867	891	0.744	2784
S7	0.25	0.924	853	0.829	2662
S8	0.33	0.985	815	0.927	2537

*Heat Stored, ΔQ is related to 1 cm thickness and 1 m^2 surface application area for a one °C temperature increase in the surface of the screed layer.

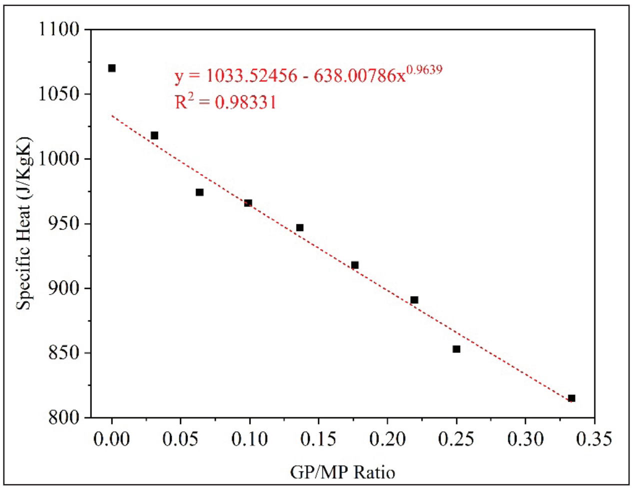

Figure 9. Relation between the GP/MP ratio in SLCS mixtures and specific heat of SLCSs.

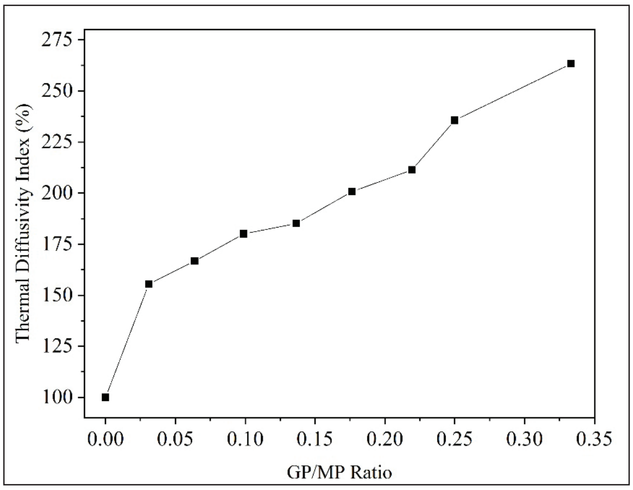

Figure 10. Thermal diffusivity indices of SLCSs as a percentage of reference screed.

are given in Table 3. The test findings pointed out that the specific heat of the reference mixture, which may be considered conventional screed mortar without any CF and GP, was 1070 J/kgK. Besides, the heat of hardened SLCS specimens using significant GP decreased from 1018 to 815 J/kgK. It is aimed to increase the specific heat value in cement-based materials, which are required to provide thermal insulation properties [29]. These types of materials can gain the ability to absorb heat from the environment where it is used. The opposite effect is desired in screeds with increased thermal conductivity rather than thermal insulation. It aims to produce products with lower specific heat values in thermal conductive materials. It was observed that the specific heat values of the screed mortars produced for underfloor heating systems decreased with the increase in the GP/MP ratio (see Figure 9). The specific heat value of a hardened mortar is the amount of heat necessary to increase the temperature of the unit mass by one degree in a given temperature environment. The lower the specific heat, the less energy is used to heat that mortar. In this regard, it can be concluded that the SLCSs produced in this study are efficient in this context.

The findings of the thermal diffusivity (α) of the SLCS specimens are given in Table 3. The test results indicate that the thermal diffusivity of the reference mixture, which may be considered a conditional screed mortar without any CF and GP, was 0.352 x10^{-6} m^2/s. On the other hand, the thermal diffusivity of hardened SLCS specimens using, especially GP, was eased from 0.547 to 0.927 x10^{-6} m^2/s. The typical values of ordinary concrete rearrange between 0.55 and 1.55 x10^{-6} m^2/s, depending on the aggregate type used in the concrete [32]. In their study, Howlader et al. [33] determined the thermal diffusivity in concrete with a density range of 1922-2339 kg/m^3 to be between 0.568 and 1.006 x10^{-6} m^2/s. They also concluded that thermal diffusivity increases with increasing density. A material with high thermal diffusivity allows for rapid heat transfer due to its ability to conduct heat efficiently compared to its volumetric heat capacity or "thermal bulk" [33]. When the analysis results are evaluated, it can be observed that increasing the GP using rate increases the heat diffusion through the screed mortar structure. This phenomenon can be assessed as heat is transferred much faster through the material in the application case, and the material will exhibit a more conductive structure for heat passages. Thus, the more heat diffused, the lower the insulation property for heating purposes in a material structure. In Figure 10, the thermal diffusivity indices of the screed mortars are given as the percentage of the thermal diffusivity index value of the reference screed. The thermal diffusivity of the reference screed was 0.352 m^2/s (i.e., 100%). The thermal diffusivity indices of SLCSs were increased with increasing MP replacement levels of GP, in other words, the GP/MP ratio. Although the thermal diffusivity indices of SLCSs were all higher than that of the reference mixture, the most noticeable jump was seen in the S1 screed by adding GP to the screed mortar design. Then, it is observed that the increase in thermal diffusivity is close to linear as the GP/MP ratio increases. Thus, in the test specimens, the heat spreads more rapidly in the screed layer, causing the surface temperature to rise even more. This study found that despite the decrease in density with the increase of graphite and carbon fiber, the thermal diffusivity has increased due to the superior conductivity characteristics of these materials.

Also, it could be concluded from Table 3 that specimens' heat storage capacity is decreasing from 4050 to 2537 calories (see Figure 11). According to Figure 11, a lower amount of heat is required to increase the temperature on the surface of the screed mortar layer by 1 °C in the context of the increased thermal conductivity value depending on the graphite additive amount of the screed mortar. This means that the heat value of the screed surface can be increased with lower heat energy consumption in the screed mortar with a high thermal conductivity value.

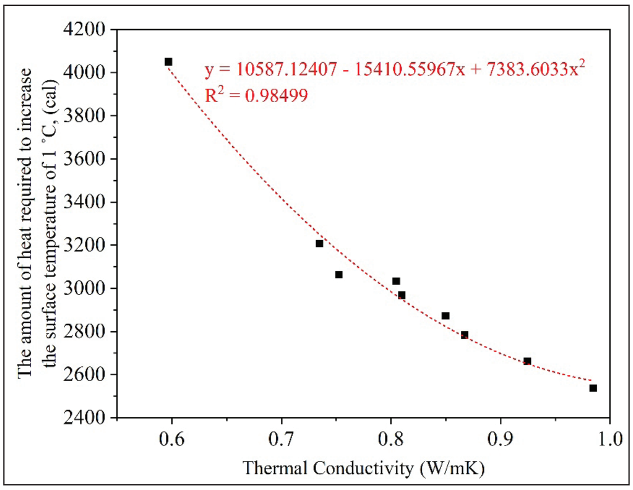

Figure 11. Relation between the amount of heat required to increase the surface temperature of 1 ˚C and the thermal conductivity of SLCSs.

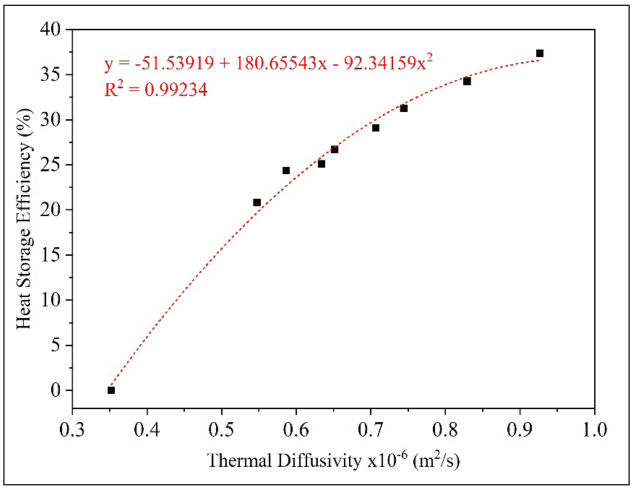

Figure 12. Relation between heat storage efficiency and thermal diffusivity of SLCSs.

Therefore a more energy-efficient heating environment can be provided. When a heat source emits heat through a material, some heat reflects from the surface, and some heat transfers through the material to the other side; moreover, some heat is absorbed in the material and stored. This stored heat should be as low as possible to make an efficient screed mortar. The heat storage capacity varies depending on the specific heat and density of the material. Because the specific heat values of the specimens produced in this study were relatively low, their heat storage characteristics were also low because of their low density and specific heat. In the experiments, the produced specimens (S1–S8) were stored at a heat of 1.26 to 1.60 times lower than the reference/nearly conventional screed mortar specimen (S0). This means that less heat energy is consumed by SLCSs (from S1 to S8). Applying this type of screed mortar to underfloor heating systems may create less heat storage capacity and contributes to energy saving by preventing the heat consumption by the screed material when energy is used to heat the indoors. Figure 12 shows the heat storage efficiency of the SLCSs with thermal diffusivity values. This graphical relationship shows that with the increase in the heat diffusion performance of the screed mortar due to the increasing amount of graphite additive, the screed surface temperature can increase rapidly by storing less heat in the screed layer. The general phenomenon expected in materials with high thermal diffusivity is that allowing heat flow in the application section layer without storing heat in their body enables the heat to pass through the section thickness quickly and increase the surface temperature in a short period. In the context of the findings obtained within the scope of this study, as the graphite ratio in the screed mortar composition increases, the heat flow performance of the screed material increases, and a lower amount of heat is stored in the body, allowing the heat to be transported to the surface quickly. This naturally causes an increase in the screed surface temperature value.

3.3. Performance of the Basic Underfloor Heating System

An experimental underfloor heating system setup was built, as shown in Figure 6. As the time elapsed from the start of heating, the water was heated for the first 4 hours, and when the maximum water temperature of 45 °C was reached, the heating of the water was cut off, and the existing hot water was circulated in the pipe. In Figure 13, T_2 temperature change analysis of S0, S1, S4, and S8 screed mortars against T_1 temperature change over 8 hours. The temperature profiles highlighted that temperature rises quickly for all screed specimens in the first 20 to 30 minutes. This indicates a significant energy transfer to the screeds in this period. After that time, the temperature continued to increase at a slower rate. However, in this second phase, the SLCS test specimens' temperature increasing rate is also higher than the S0 reference screed mortar. When the figure is analyzed, it can be easily observed that the surface temperature of the S0 (reference/conventional) screed is lower than that of the hot water pipe. In SLCS test specimens, the situation is reversed, and the difference between the temperature of the outer surface of the hot water pipe (T_1) and the temperature of the screed surface (T_2) decreases considerably. This means the SLCS specimens perform pretty well compared to the reference specimen in conducting heat and reducing heat losses. In addition, although the heating of the circulating water in the pipe is stopped after the 4th hour, it is observed that the cooling rate of the SLCS test specimens after this moment is relatively slow. The surface temperature of the S4 and S8 specimens was higher than the pipe surface temperature at the 7.5th and 8th hours. This shows how late the screed mortars cool down and retain heat.

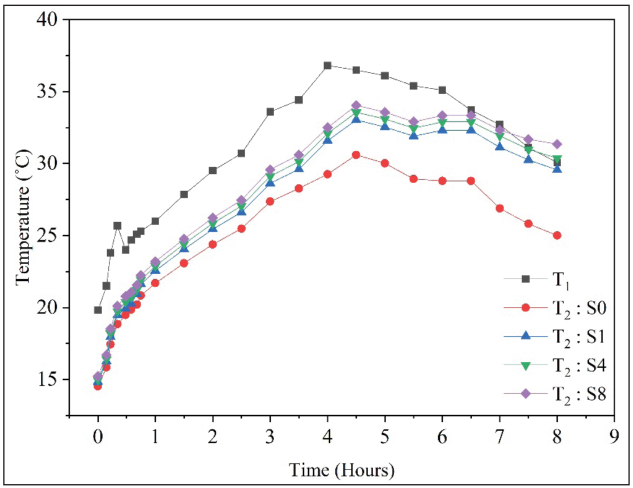

Figure 13. T_2 temperature change of S0, S1, S4 and S8 screeds versus T_1 temperature change over time.

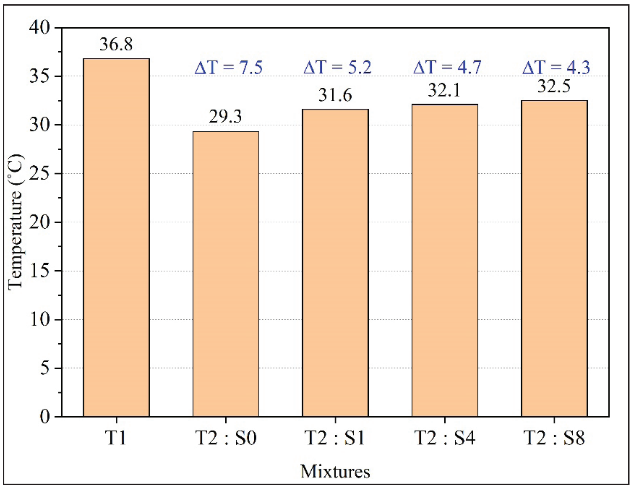

Figure 14. T_2 temperature change of S0, S1, S4 and S8 screeds versus T_1 temperature change at T_w is maximum.

A comparison of the T2 temperatures of SLCS mortars and T1 temperature is given in Figure 14. In this analysis, the results when T_w reaches 45 °C are shared. As it can be easily noticed from the figure, when the circulating water is 45 °C, the outer surface temperature of the hot water pipe is measured as 36.8 °C. The outer surface of the reference screed (S0) was measured at 29.3 C, while the temperature loss between T_1 and T_2 was determined as 7.5 °C. In SLCS specimens, the temperature loss between T_1 and T_2 temperatures decreased and was defined as 5.2, 4.7, and 4.3 °C in S1, S4, and S8 specimens, respectively. Farid & Kong [34] used phase change materials in concrete and modeled an underfloor heating system by using this concrete above hot water pipes. According to their study, the concrete slab varied in its surface temperature between 22.5 and 36.5 °C for three days (a 24 h cycle of 8 h heating followed by 16 h heat discharge). Thermal properties of screed mortars, which are high thermal conductivity, thermal diffusivity, and low specific heat and heat stored, are critical factors in the efficiency of the underfloor heating systems.

4. CONCLUSIONS

This study presented the results of an experimental work on developing a new type of screed mortar. It analyzed the result of applying screed mortars on a basic underfloor heating system as a floor slab finishing material.

The experimental test showed self-leveling lightweight composite screeds obtained 1303-1319 kg/m^3 densities. Besides, although the compressive strength of the mortars decreases as the graphite ratio in SLCS mixes increases, the compressive strength of the 14.51-18.37 MPa range was obtained, which is well above the minimum lower limit of 5 MPa compressive strength specified in the relevant standard.

In the first stage of the study, the thermal properties of the screed mortars were analyzed and compared with a reference (nearly conventional) screed mortar. According to the results, in SLCS test specimens, adding carbon fiber and significantly increasing the graphite ratio increased the thermal conductivity by up to 65 %, and the highest thermal conductivity value was determined as 0.985 W/mK. Similarly, it was observed that thermal diffusivity increased by 163% compared to the reference screed mortar. It has been observed that the specific heat values of SLCS specimens can decrease up to 23.83% compared to the reference mortar. Thus, less energy would be used to heat those screed mortars. Similarly, the amount of heat required to increase the surface temperature of 1 °C and thermal conductivity of SLCSs were decreased as the graphite ratio increased in the test screed mortars.

In the second stage of the study, an experimental underfloor heating system setup was built. The temperatures of the water circulating in this system, the outside of the pipe carrying the water, and the surface of the screed were measured at specific intervals. It can be accepted that the closer the temperature of the outer wall of the pipe carrying the hot water and the temperature of the screed surface is, the better the system's efficiency. According to the results of time-dependent temperature values taken from different system parts, SLCS test specimens can heat up faster and retain their heat for longer than the reference screed. Moreover, while there was a loss of 7.5 °C between the pipe outside temperature and the screed surface temperature in the reference sample when the water temperature was maximum, this value was measured as only 4.3 °C in the S8 test screed mortar.

In this experimental study, it has been determined that self-compacting screeds in composite structures produced with different pozzolanic, chemical, reinforcement, and filling materials can be used effectively in underfloor heating systems.

Based on the findings of this study, the combined use of graphite and carbon fibers can be recommended for screeds to be used in underfloor heating systems. However, since an increase in the graphite content leads to decreased compressive strength, the content should be controlled (with a minimum compressive strength of 4 MPa according to the standard). Similarly, the carbon fiber content should be increased in a controlled manner as it directly affects the self-leveling property. According to the results of this study, even though the addition of carbon fiber and increased graphite content reduces the density of the mortar, the conductivity values have improved. Moreover, the high incorporation of carbon fiber and graphite can be recommended due to meeting the desired limit values for mechanical properties.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

All graphs and data obtained or generated during the investigation appear in the published article.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Author #1 Şevket Onur Kalkan: Drafted and wrote the manuscript and performed the experiment and result analysis. The planned methodology concludes.

Author #2 Lütfullah Gündüz: Supplied the materials and designed the experimental setup. Supervised the experiment's progress and helped in manuscript preparation.

PEER-REVIEW

Externally peer-reviewed.

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