

## Research Article

# Combined Effects of Graphite Tailings and Curing Conditions on the Early-Age Performances of Cement Mortar

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In this study, the combined effects of different amounts of graphite tailings (GT) as a substitute for sand and three cure methods on the early-age mechanical and material performances of cement mortar have been investigated. The results can be concluded that graphite tailings and hot-water cure method can effectively improve the early strength of cement-based materials and facilitate the formation of high-density calcium silicate hydrate (C-S-H), more  $\text{Ca}(\text{OH})_2$  (CH), and other hydration products. Simultaneously, the pore structure distribution in the cement mortar is improved to be finer. Finally, this paper explains the mechanism of GT and hot-water curing (HWC) method on early-age performances of the cement mortar through the graphic model and provides the basis for selecting the GT and HWC method on improving early performance requirements for special engineering or rapid repair engineering through the proposed comprehensive quantitative calculation model.

## 1. Introduction

Cement-based materials are the most widely used building materials worldwide. In recent decades, the composition and characteristics of cements, such as the hydration process, mechanical properties, durability, workability, material properties, pore structures, and C-S-H content, have been extensively studied from a physical and chemical perspective [1–3]. Of the various properties, early performance is of increasing interest. Research on the early strength of cement-based materials is important for several reasons [4–8]: (1) increasing the early strength can shorten the construction period and accelerate the use of building formwork or improve the use of the formwork, which is conducive to the economic sustainability of building construction projects. (2) For major engineering or military engineering applications, early-strength cement-based materials can meet engineering service conditions or military requirements. (3) Early-strength cement-based materials are of great significance for the repair, reinforcement, and renewal of airport

runways, expressways, ports, and terminals. (4) The study of the early strength property also provides a basis and support for high-strength concrete, high-performance concrete, or ultrahigh-strength concrete. The work was driven by the military, important projects, mass production, and industrialization requirements for building materials to be ready rapidly and in an economical way. The performance of cement-based materials at an early time and their immediate use are the result of scientific research, engineering needs, and the industry developments [9–12].

The early quality of cement-based materials depends mainly on the composition and the curing conditions [13]. There are several methods to obtain early strength in concrete or cement mortar. One effective way is to change the curing method, such as using a hot-water curing method, boiling-water curing method, autogenous curing method, changed hot-water curing method, microwave curing method, accelerated curing method, and combination curing method (traditional method with the accelerated curing method or other methods) [14–18]. The accelerated

curing methods that are applied during actual engineering applications are very limited [19]. Furthermore, some curing methods, such as boiling-water curing or autogenous curing without effective hydration, can result in significant disadvantages. For example, the compactness and workability of cement-based materials can be adversely impacted, inhomogeneous hydrate products can be formed, and the heterogeneity of the material matrix can be increased, which affect the pore structure distribution and crack density, resulting in a decreased comprehensive performance. Therefore, on the basis of changing the curing method, the aforementioned deficiencies can be addressed by using fine materials, such as an admixture, a cementitious material, or a fine aggregate, such as silica fume, fly ash, steel slag, or tailings. Fine materials can not only improve the early performance of cement-based materials but also contribute to green development through the reuse of solid waste and reduction in the consumption of construction raw materials [20–30]. These benefits collectively contribute to sustainability and economic development of green building projects.

Graphite tailings (GT) are a new type of tailing that are a Ca-Si-Fe-Al ceramic material with sufficient  $\text{SiO}_2$  and a certain amount of calcium, iron, and aluminum oxide; it is a constituent of concrete, either as an aggregate or as a cementing material, or both [31, 32]. The decreased fineness modulus and increased water absorption or water retention rate of graphite tailings can improve the performance of construction materials by replacing sand as a fine aggregate. Although some published studies on building materials containing GT have evaluated their suitability and mechanistic performance improvement or mesostructure changes, research on changing the properties of cement-based materials with GT is still in its infancy. In particular, there have been no studies conducted with a focus on the effects of incorporating GT in concrete or cement mortar for increased early strength and associated curing methods that would enable rapid construction and efficient structural use. The goal of this study is to fill these research gaps by investigating the early strength and material characteristics of cement mortar that incorporates GT as a replacement for sand as a fine aggregate and is subjected to different curing conditions. Flexural and compressive strength were measured to evaluate the impact of the GT on the macro-performance, material morphology, hydration products, and pore structure; the functional groups were investigated to determine the mesoscopic properties during different curing schemes. Finally, a schematic model was used to explain the mechanism of the impact of GT on the early performance of cement-based materials. Simultaneously, the optimal curing method and the amount of GT are also proposed in this paper to quantify the impact of GT and curing methods on cement-based materials, special engineering, or rapid repair engineering.

## 2. Materials and Experimental Methods

The experimental plan is shown in Figure 1, and the test details are as follows.

### 2.1. Materials

**2.1.1. Raw Materials and Mixing Proportions.** Ordinary Portland cement (P.O 42.5), local river sand with a fineness modulus of 2.3, GT with a fineness modulus of 0.9, and groundwater were used throughout the experiments. The graphite tailings used in this study were from Jixi, China (longitude  $130^{\circ}24'24''$ , north latitude  $44^{\circ}51'12''$ ). The apparent comparison of GT and river sand is shown in Figure 2. The laser particle size distribution and granular gradation of the GT and sand are shown in Figure 3. Tables 1–3 list the mechanical properties of the cement, the chemical properties of the cement, sand, and graphite tailings, and the mineral content of cement and graphite tailings, respectively. The physical properties of river sand and graphite tailings are listed in Table 4. In summary, the physical and chemical properties of GT and sand are similar, and its appearance is similar to sand. The main minerals (mass content) in GT are quartz (79.7%), clay (7.4%), biotite (8.6%), graphite (0.02%), and others. The content of graphite in the GT was 0.02% by mass, and GT was only determined through a sieve. At the same time, by comparing its apparent morphology, physical and chemical properties, harmful components, etc., GT can be regarded as thin, nonpolluting, and pollution-free sand that can be used as a building material.

In this study, the graphite tailings replaced river sand in different volume ratios, such as 0–40%, the water-to-cement ratio (w/c) was 0.4, and the binder-to-sand ratio (b/s) was 1.5. The mixing proportions of the graphite tailing-cement mortar (GTCM) specimens are listed in Table 5, and slump of all the test specimens meet the requirements of the building materials.

**2.1.2. Specimen Casting and Curing Conditions.** The GTCM specimens had dimensions of  $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$  and were demolded after 24 h in accordance with the Chinese standard GB/T 17671-1999 [33]. The curing schemes are listed in Table 6. The standard curing method (SC method) is performed in a steam curing room with a temperature of  $20 \pm 2^{\circ}\text{C}$  and a relative humidity of 95%, and the hot-water curing method (HWC method) is performed in a water bath apparatus (HH-F). The combination curing method (CC method) includes the aforementioned two methods as follows. (1) For 1 day, the demolded specimens were cured in a steam curing room for 12 h and in a water bath apparatus for 12 h at  $60^{\circ}\text{C}$ . (2) For 3 days, there are two methods. The first method involved the demolded specimens being cured in a steam curing room for 1 day and in a water bath apparatus for 2 days at  $60^{\circ}\text{C}$  (CC: 1-2). The other method involved the demolded specimens being cured in a steam curing room for 2 days and in a water bath apparatus for 1 day at  $60^{\circ}\text{C}$  (CC: 2-1).

### 2.2. Experimental Methods

**2.2.1. Mechanical Property Test.** A total of 400 GTCM specimens were prepared for the compressive and flexural strength tests using a cement mortar flexural and

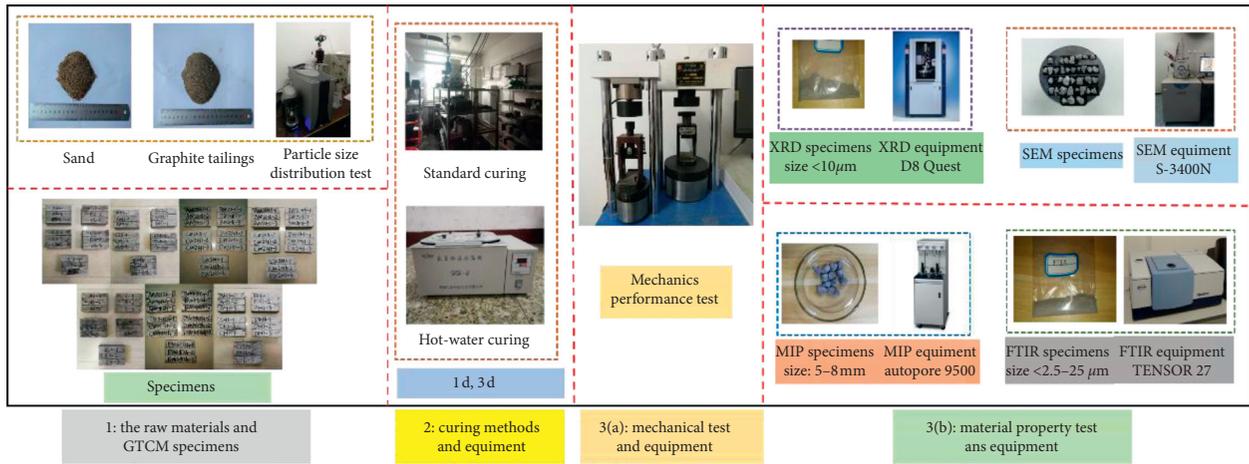


FIGURE 1: Flowchart of experimental methods.

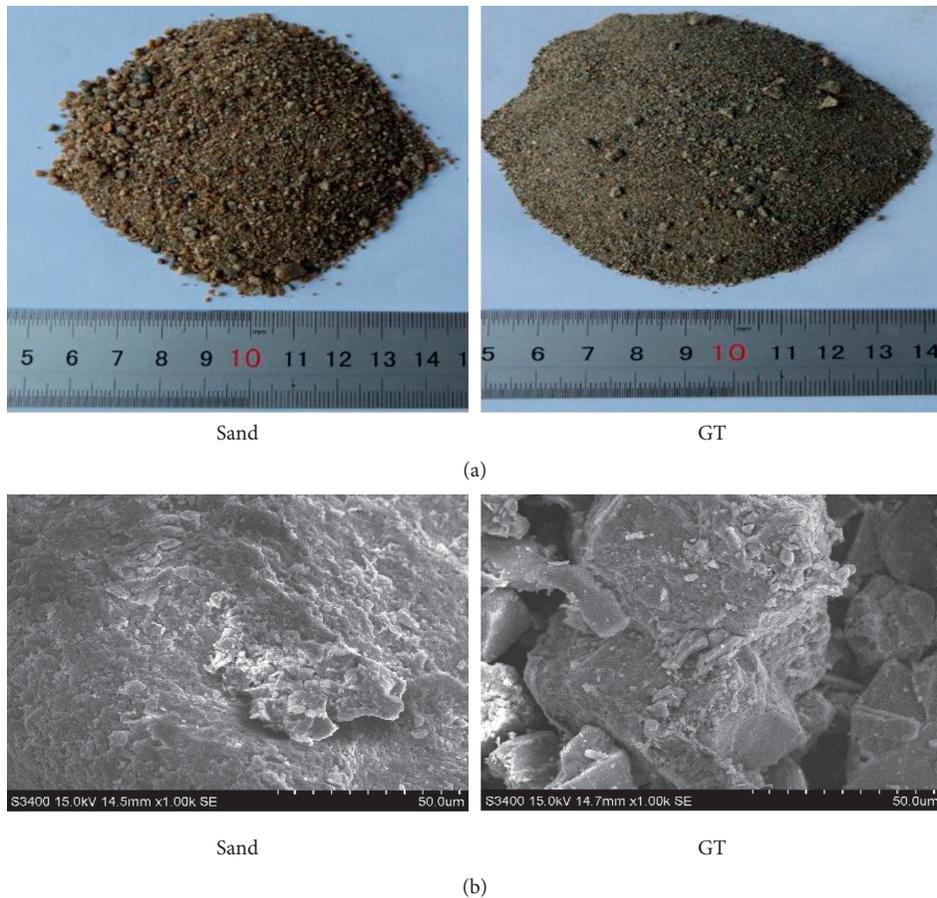


FIGURE 2: The apparent comparison of GT and sand: (a) apparent comparison; (b) SEM comparison.

compressive constant stress testing machine (HYE-300B) according to JTG E30-2005 [36].

**2.2.2. Material Characterization Tests.** To further explore the effect of the GT on the early performance of cement mortar under the action of different curing conditions,

several experimental methods were applied. Sixty samples were subjected to mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) to analyze the changes in the pore structure distribution, mesomorphology, hydration products, and chemical bonding or molecules in the GTCM specimens subjected to

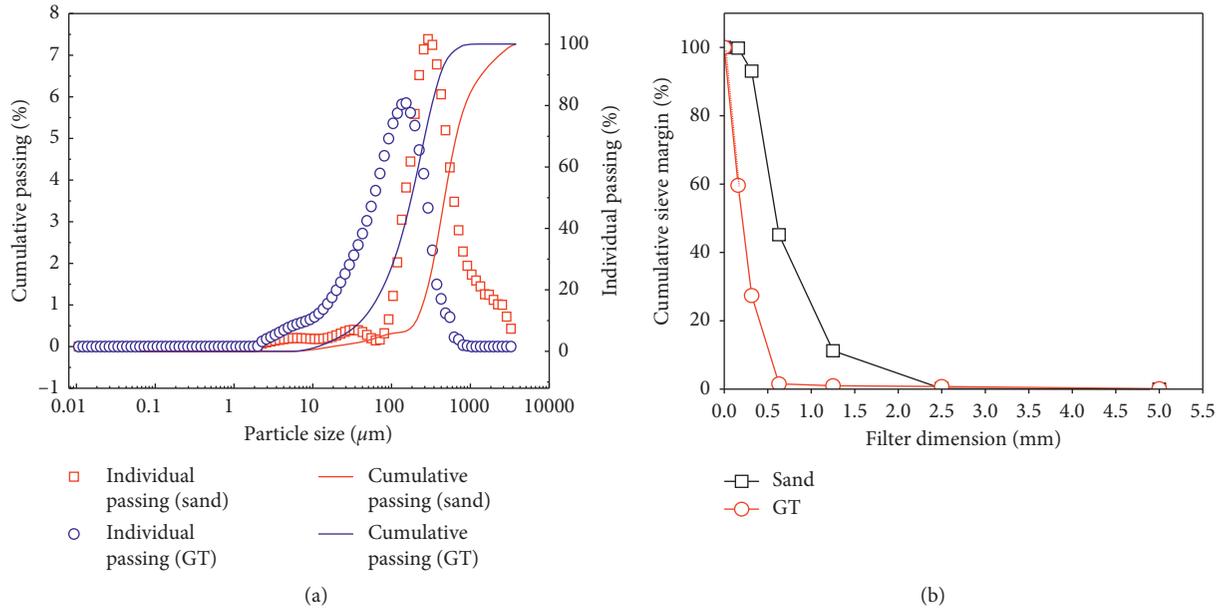


FIGURE 3: Particle size distribution and granular gradation of GT and sand: (a) particle size distribution; (b) granular gradation.

TABLE 1: Mechanical properties of Portland cement (MPa).

Flexural strength (MPa)		Compressive strength (MPa)		Fineness	Setting time (min)	
3 days	28 days	3 days	28 days		Initial setting	Final setting
4.1	9.3	21.2	46.1	1.2	164	272

TABLE 2: Chemical properties of Portland cement, sand, and graphite tailings (%).

Materials	Chemical compositions									
Cement	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	SO <sub>3</sub>	Loss			
	59.64	21.47	5.80	4.04	3.24	2.08	2.44			
GT	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	SO <sub>3</sub>	V <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Loss	
	15.55	62.50	10.21	5.07	2.33	0.54	0.42	2.26	1.17	
Sand	SiO <sub>2</sub>	Loss								
	99.80	0.02								

TABLE 3: Mineral content of cement and graphite tailings (%).

Cement	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>4</sub> AF	C <sub>3</sub> A	Gypsum	Semiwater gypsum	Impurities
	65.70	18.10	8.50	4.70	2.10	0.20	0.07
Graphite tailings	Hematite	Clay	Plagioclase	Quartz	Black mica	Impurities	LOI
	1.1	7.4	41.4	38.3	8.6	3.2	4.15

TABLE 4: Properties of sand and graphite tailings.

Type	Natural stand	Graphite tailings
Size (mm)	0.16–5	0.2–0.4
Apparent density (kg/m <sup>3</sup> )	2,620	2,855
Bulk density (kg/m <sup>3</sup> )	1,630	1,540
24-hour water absorption (%)	21.8	36.7
Fineness modulus	2.49	0.90
pH value	7.0	10.0

TABLE 5: Mixing proportions of GTCM (kg/m<sup>3</sup>).

W/C = 0.4	Cement	Water	Sand	Graphite tailings	Superplasticizer (%)
GTCM-0	689.70	275.90	1034.50	0	0.05
GTCM-10	689.70	275.90	931.05	103.50	0.05
GTCM-20	689.70	275.90	827.60	206.90	0.06
GTCM-30	689.70	275.90	724.15	310.35	0.11
GTCM-40	689.70	275.90	620.70	413.80	0.26

TABLE 6: Curing schemes of GTCM.

Curing schemes	Curing method abbreviation	Curing days	Curing temperature	Relative humidity (RH)	Note
Standard curing	SC [33]	1 d, 3 d	20°C	95%	Curing 1 d and 3 d
Hot-water curing	HWC [34]	1 d, 3 d	60°C	100% (in water)	Curing 1 d and 3 d 1 d: 20°C-12 h + 60°C-12 h
Combined curing	CC [35]	1 d, 3 d	20°C + 60°C	100% (in water)	3 d: 20°C-1 d + 60°C-2 d 3 d: 20°C-2 d + 60°C-1 d

different curing methods. The preparation and drying conditions of these samples were in accordance with Chinese regulations GB/T 21650-2008 [37], GB/T 16594-2008 [38], GB/T 30904-2014 [39], and ISO 19618-2017 [40].

### 3. Results and Discussion

**3.1. Mechanical Properties of the GTCM.** The flexural strength is the most critical material property of cement mortar and determines its engineering application and development prospects. In this paper, experimental results of the flexural strength of the GTCM specimens with different curing methods are shown in Figure 4. (1) After curing for 1 day, the order of influence of three curing methods on the development of the GTCM flexural strength is HWC > SC > CC, and the flexural strength of the cement mortar is well developed with the HWC method. Although the HWC method is also present in the CC method, the flexural strength cannot be sufficiently developed due to the insufficient curing time in hot water. Therefore, the HWC method is most beneficial for quickly improving the 1-day flexural properties of cement mortar. Simultaneously, GT has a significant influence on the flexural strength with each curing method. With an increasing amount of GT, the flexural strength obviously increases and then slightly decreases with the HWC method, but the flexural strength has a nonlinear trend with the SC and CC methods, especially when the GT content is 40% in the CC method, where the flexural strength is the lowest.

When the amount of graphite tailings is appropriate, the cement mortar is denser. That is, the distance between aggregates and the distance between aggregates and cement particles are smaller. With curing time increasing, the unhydrated particles are decreasing, and then hydration production is increasing in the whole hydration reaction. If the cement mortar is always cured by SC or HWC, the rate of decreasing unhydrated particles and increasing hydration production is similarly increasing. However, hot-water conditions have a great advantage in stimulating GT activity and improving the performance of the cement mortar after 1

day. However, when the graphite tailing content is 40%, the particles in cement mortar are so dense that the space of increased hydration production is slightly more than the space of decreased unhydrated particles. During the standard curing process of the front part of the combined curing, C-S-H is generated, which is located between unhydrated particles and water required for the hydration reaction, which slightly hinders the diffusion of cement particles such as tricalcium silicate in solution [41]. During the hot-water curing process in the later stage, the growth rate of C-S-H is greater than the reduction rate of unhydrated particles. This phenomenon causes weak internal stress in the mortar, resulting in a reduction in flexural strength which is more sensitive to this phenomenon than compressive strength. After one day of combined curing, the reduction of flexural strength does not exceed 0.4 MPa. When the combined curing is performed for three days, the standard curing time is longer, increasing the time for cement particles to dissolve and react, leaving space for the generation of hydration products. When hot-water curing begins, hydration products are accelerated to fill the pores between the particles, and the strength is improved.

The combined effect of the HWC method and a GT content of 20% shows the best improvement for the synergistic development of the flexural strength of the GTCM after 1 day, and the maximum value is 7.6 MPa. (2) The 3-day flexural strength is significantly affected by the combined influence of the GT and curing methods. The HWC method also improves the mechanical properties of the GTCM, especially in combination with the incorporation of GT. For the GT incorporation of 10% to 40%, the combination of the HWC method and GT improves the flexural strength of the GTCM. When the GT incorporation is 20% and the HWC method is used, the flexural strength of the GTCM reaches a maximum value of 10.8 MPa. In addition, when the GT incorporation is 20% and 30% and the CC: 2-1 method is used, the flexural strength can be improved, although the improvement is smaller compared with the HWC method. However, the combination of the SC method and GT incorporation results in a very small

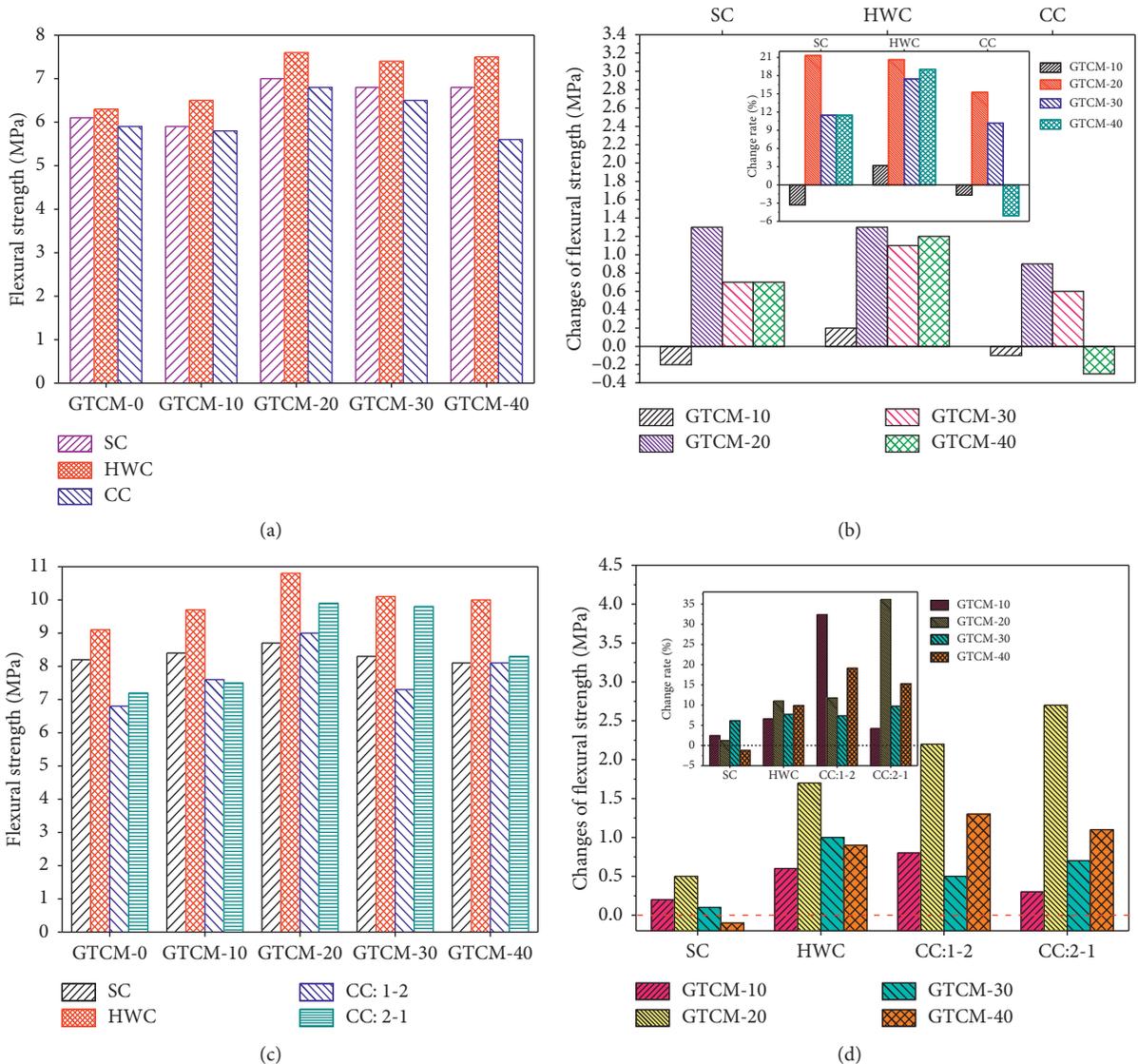


FIGURE 4: Flexural strength of GTCM under different cure methods: (a) 1 day; (b) changes of 1 day; (c) 3 days; (d) changes of 3 days.

change in the flexural strength, and the flexural strength for 30% and 40% GT incorporation is inferior to that of the pure cement mortar.

Another major mechanical indicator for cement mortar is the compressive strength. The compressive strength of the GTCM is shown in Figure 5. The results show that the HWC and CC methods have a significant effect on the development of compressive strength. However, the SC method has an inhibitory effect on the development of the compressive strength of the GTCM, especially when the GT incorporation is greater than 20% at 3 days. The maximum compressive strength of the GTCM is for a combination of 20% GT and the HWC method, and the values are 39.8 MPa for 1 day and 51.3 MPa for 3 days. In summary, the GT and HWC methods have an important impact on the mechanical properties of GTCM. For emergency engineering, repair, and reinforcement projects, construction of critical structures or high-performance building materials, the incorporation of 20% GT and the use of the HWC method, is the

best way to improve the mechanical properties of the materials and facilitate an effective and convenient structural construction. The comprehensive mechanisms of GT and curing methods on the early performance of GTCM are further explored through mesostructure changes (Section 3.2) and quantitative and graphical models (Section 3.3).

**3.2. Material Characterization of the GTCM.** The GTCM specimens under the combined effect of 0% and 20% GT and the HWC method were selected for analysis of the 1-day and 3-day macroscopic performance changes. The SC method is commonly used in engineering, and the results of the mesocharacteristics as a result of this method were used for comparative analysis.

**3.2.1. Material Morphology of the GTCM.** Changes in the material morphology of GTCM-0 and GTCM-20 during the SC and HWC methods are determined based on SEM and

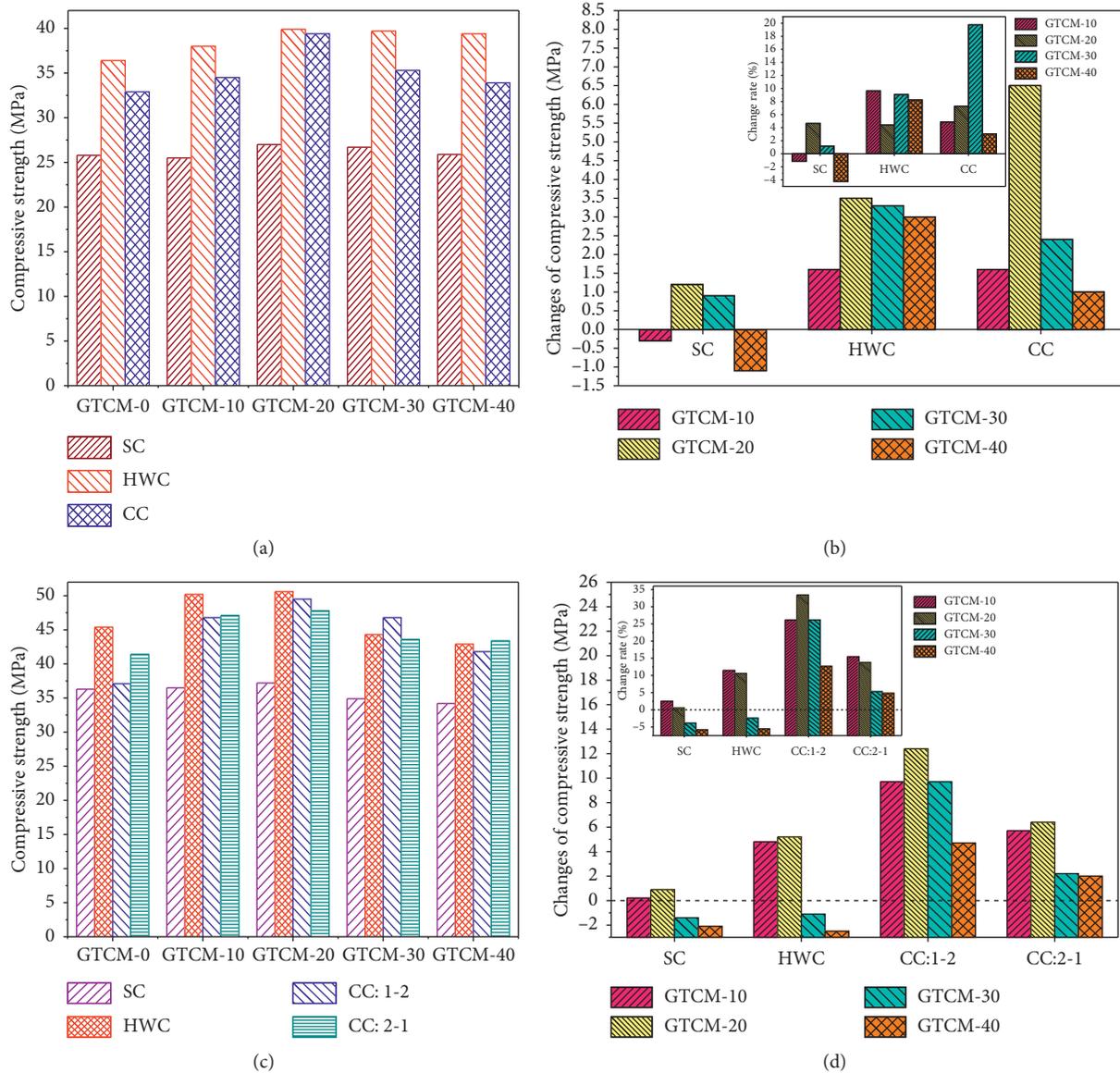


FIGURE 5: Compressive strength of GTCM under different cure methods: (a) 1 day; (b) changes of 1 day; (c) 3 days; (d) changes of 3 days.

are shown in Figures 6 and 7. There was a substantial amount of flocculating hydration products in GTCM-0 and a substantial amount of cement particles that were not involved in the hydration reaction in GTCM-20 under the SC method after 1 day. Due to insufficient hydration, cementation strength was low, and many internal defects were present in GTCM-0. At this point, the presence of the GT in GTCM-20 did not change the poor hydration state simply because the low fineness changed the internal defect density, resulting in an increase in the macroscopic strength compared with GTCM-0. The hot-water condition partially improved the unhydrated state in GTCM-0, the flocculating hydration product decreased, and the solid hydration product increased. At the same time, the unhydrated cement particles in GTCM-20 almost disappeared, and a relatively complete solid and filamentous hydration product was formed. The combination of GT and hot water made the cement mortar

curing more complete after 1 day. After curing for 3 days, there was still a certain amount of flocculating hydration products and cement clinker in GTCM-0 and GTCM-20 under the SC method, but hot-water conditions can change the aforementioned disadvantages, and with the incorporation of the GT, the cement inside the cement mortar was denser. Therefore, the combination of GT and HWC can improve the shortcomings of insufficient hydration and weak cementation of cement mortar to some extent and reduce internal defects, which provides better early mechanical properties.

**3.2.2. Hydration Products in the GTCM.** The early hydration products of GTCM-0 and GTCM-20 under the SC and HWC methods are shown in Figures 8 and 9, respectively. For GTCM-0, the peak value and area of CH increase with

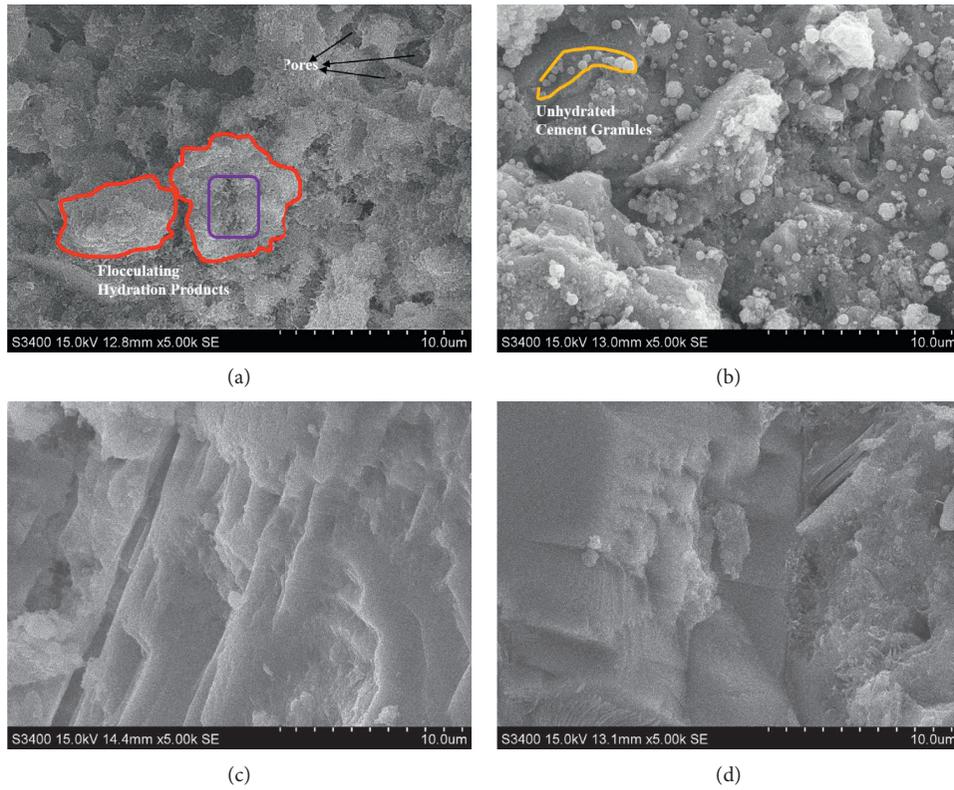


FIGURE 6: Mesomorphology of GTCM for 1 day: (a) GTCM-0 under the SC method; (b) GTCM-20 under the SC method; (c) GTCM-0 under the HWC method; (d) GTCM-20 under the HWC method.

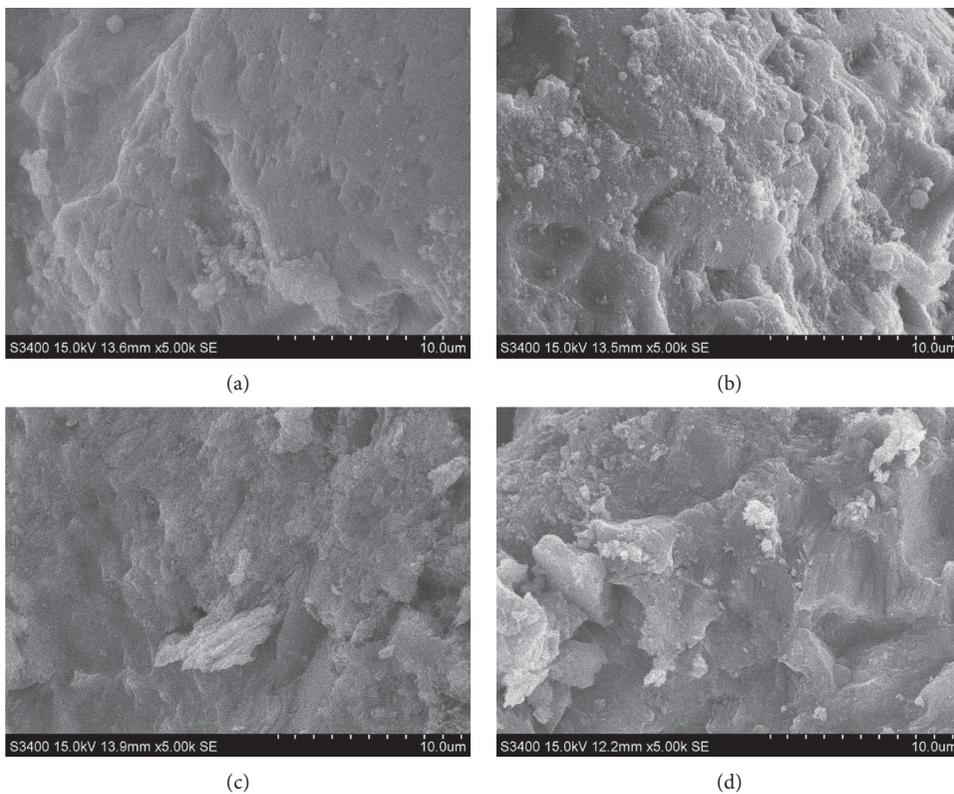


FIGURE 7: Mesomorphology of GTCM for 3 days: (a) GTCM-0 under the SC method; (b) GTCM-20 under the SC method; (c) GTCM-0 under the HWC method; (d) GTCM-20 under the HWC method.

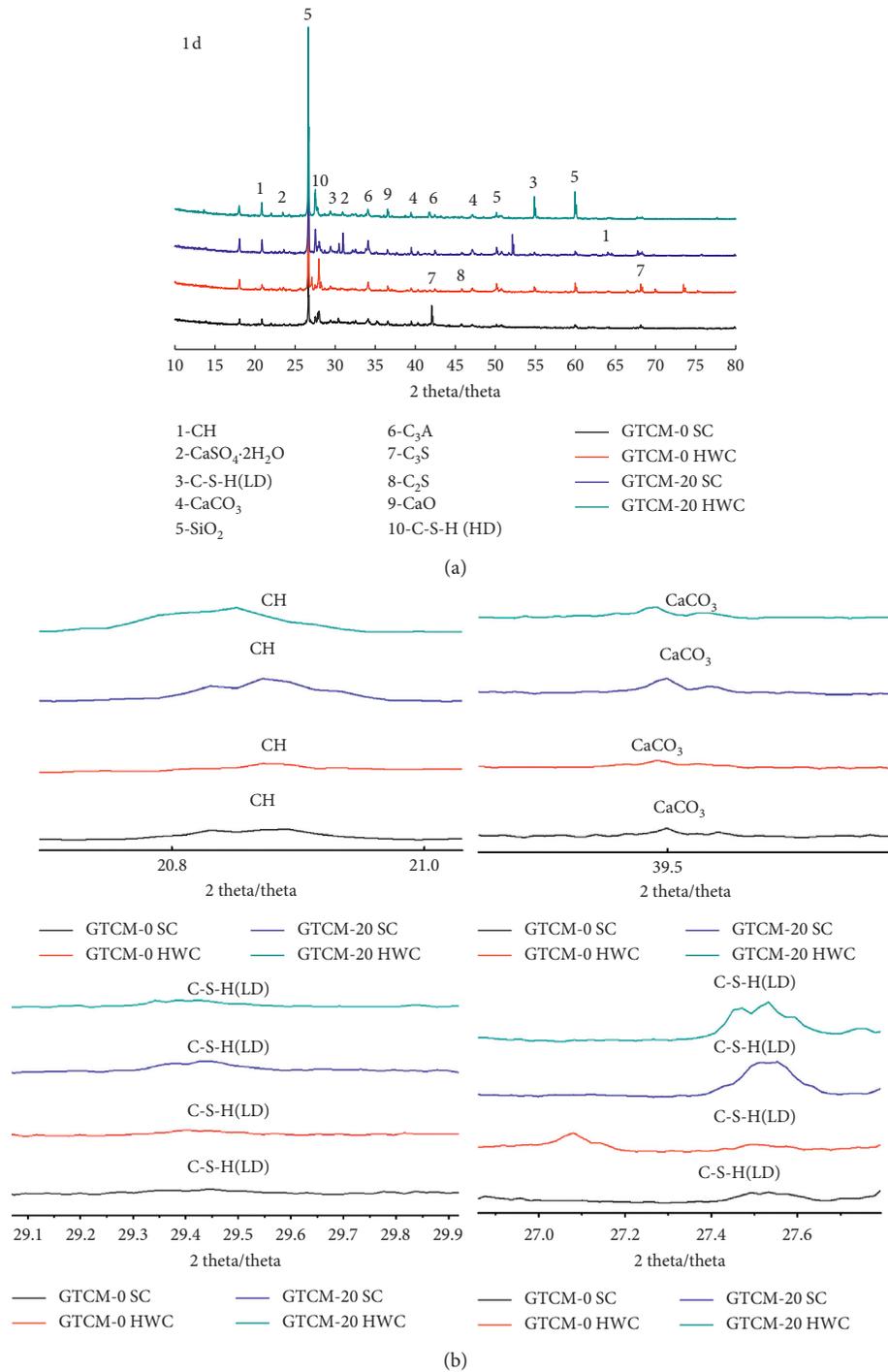


FIGURE 8: Hydration product analysis of GTCM-0 and GTCM-20 under SC and HWC methods for 1 day.

curing times from 1 day to 3 days, but the peak value and area of CH under the HWC method after 3 days are less than those of the SC method due to the accelerated precipitation as a result of the hot-water conditions. The content of the hydrated calcium carbonate product does not change significantly, and AFt appears only under 1 day of hot-water curing. When the curing time increases from 1 day to 3 days, the content of C-S-H (LD, Ca/Si < 1.5) increases, but the content of C-S-H (HD, Ca/Si > 1.5) decreases. The hot-water curing conditions significantly

increase the peak areas of C-S-H (LD) and C-S-H (HD). The change in the hydration product for GTCM-20 is different than that for GTCM-0. The peak value and area of CH in GTCM-20 increase as the curing time increases from 1 day to 3 days, and there is no significant decrease in the hot-water condition because CaO contained in the GT promotes the formation of CH to counteract the rapid precipitation of CH. The peak value of CaCO<sub>3</sub> is lower after the 1-day hot-water cure than that after the standard cure but higher than that of SC after 3 days. The

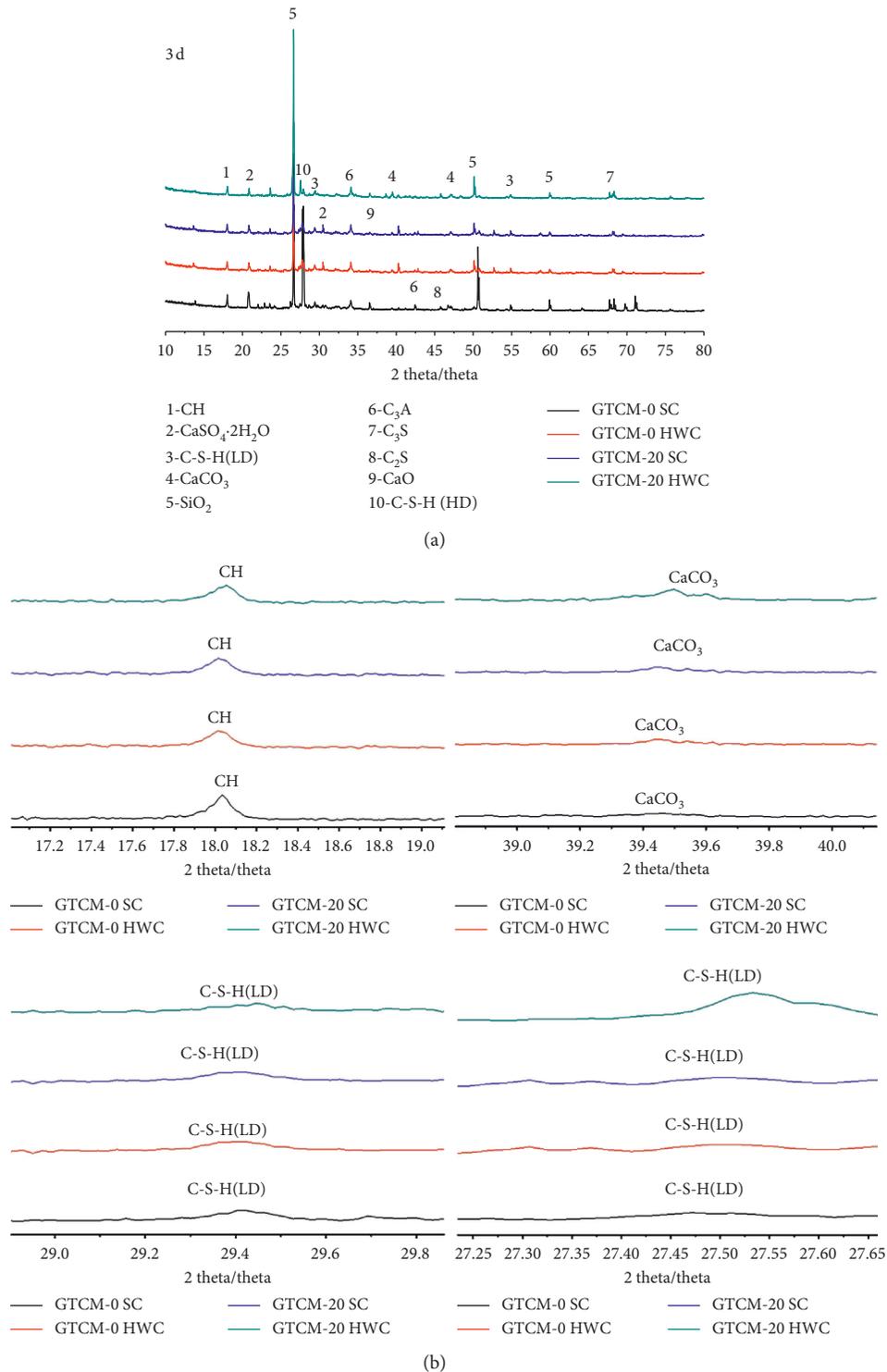


FIGURE 9: Hydration product analysis of GTCM-0 and GTCM-20 under SC and HWC methods for 3 days.

significant change in GTCM-20 is the amount of C-S-H gel produced. The GT leads to the generation of more C-S-H (HD), but AFt generation does not improve. The combination of the GT and the HWC method results in a large amount of C-S-H formation in the cement mortar after 3-day curing, which greatly solidifies the matrix and results in improved mechanical properties.

3.2.3. *Functional Group Changes in the GTCM.* In this paper, the effects of the GT and curing methods on the early performance of GTCM were also analyzed by the changes in the functional groups. The changes in the functional groups of the GTCM are determined based on FTIR and are shown in Figure 10. After 1-day curing, the contraction vibration of the -OH functional group (3644) in CH is more apparent in

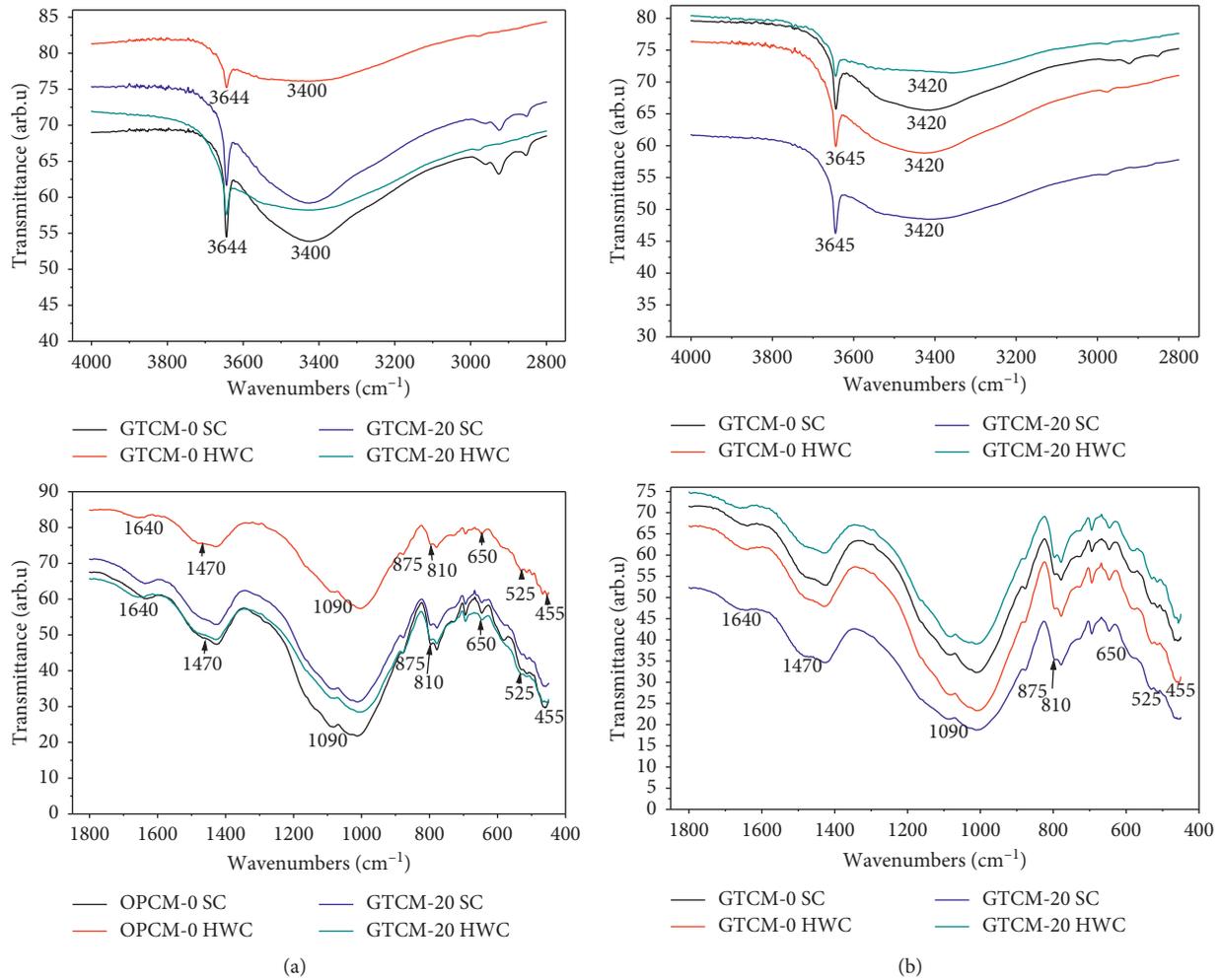


FIGURE 10: Functional group analysis on GTCM-0 and GTCM-20 under SC and HWC methods: (a) 1 day and (b) 3 days.

the SC method than in the HWC method, and the shrinkage vibration of the H-O-H (3400) functional group is not obvious in the HWC method. The bending vibration of H-O-H (1640) is not significantly affected by changes in curing methods. The acceleration of water evaporation in the matrix due to hot water or the dehydration of CH is caused only by the change in the contraction vibration of -O-H. The GT incorporation promoted the contraction vibration of the -OH functional group in CH and offsets the effect of hot water on its vibration but does not offset the effect of hot water on the -O-H functional group in the aqueous phase and even reduces its vibration. Simultaneously, GT also reduces the intensity of the Si-O stretching vibration absorption peak in the Q3 tetrahedron (650). However, the width of the Si-O-Si bending vibration band increases so that the Si-O-Si bond angle and the polymer increase, and Ca/Si of the hydration product reaches 1.19 (the vibration intensity is lowered to indicate that  $Ca/Si \geq 1.19$ ) rapidly. When the curing time is 3 days, the incorporation of the GT improves the contraction vibration of the -OH functional group in CH, and the HWC method does not reduce the vibration of CH or the bending vibration of H-O-H in GTCM-0 but

significantly reduces them in GTCM-20. The Si-O out-of-plane bending vibration absorption peak (525) and the Si-O in-plane bending vibration absorption peak (455) vary significantly under the combined effect of the GT and HWC method; that is, the degree of polymerization of the cementitious material gradually increases with the hydration process to form a C-S-H gel with an increased density.

**3.2.4. Analysis of the Pore Structure Distribution in the GTCM.** The pore structure distribution, porosity, total pore volume, pore area, and pore percentage in the GTCM during different curing methods after 1 day and 3 days are shown in Figure 11 and Table 7. The cumulative pore volume percentage is shown in Figure 12. The cumulative pore volume percentages are divided according to the principle of harmless pores (<20 nm), less harmful pores (20–100 nm), harmful pores (100–1000 nm), and very harmful pores (>1000 nm). The results show the following. (1) After 1 day, the main peak in the pore size distribution of GTCM-0 and GTCM-20 moved from 62.5 nm to 26.2 nm, respectively; it changes from 62.1 nm to 21.2 nm for the SC to HWC

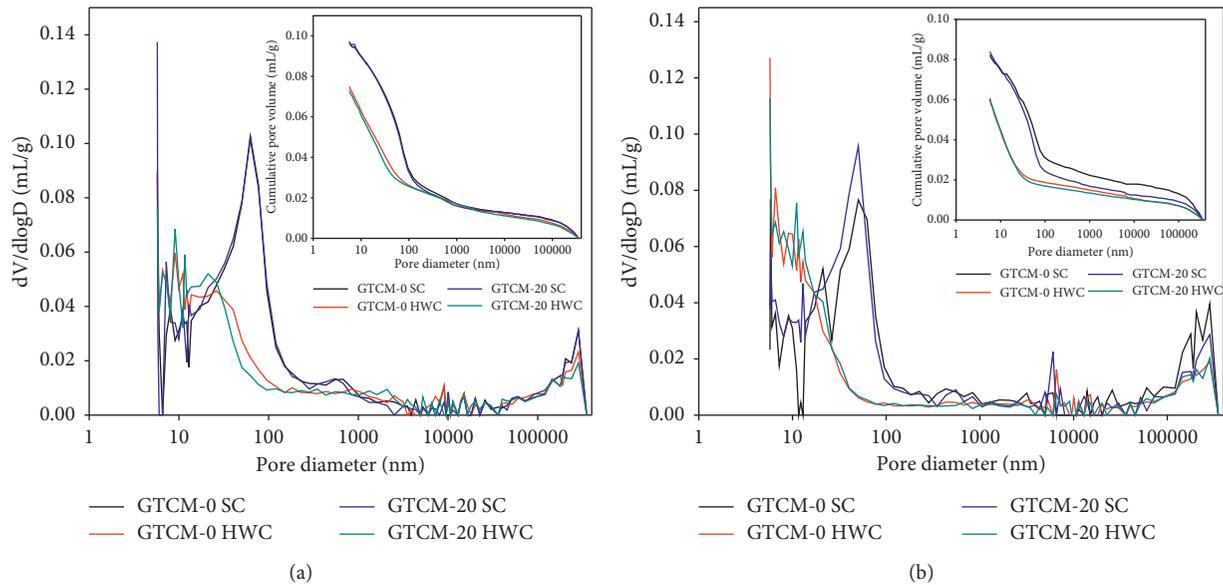


FIGURE 11: Pore size distribution of GTCM-0 and GTCM-20 under SC and HWC methods: (a) 1 day and (b) 3 days.

TABLE 7: Porosity, total pore size, and area of GTCM-0 and GTCM-20 under SC and HWC methods.

Age (d)	Specimen number	Curing scheme	Porosity (%)	Total intrusion volume (mL/g)	Total pore area (m <sup>2</sup> /g)
1	GTCM-0	SC	19.1284	0.097	11.162
		HWC	14.9371	0.075	13.134
	GTCM-20	SC	19.0719	0.097	11.086
		HWC	14.7349	0.073	13.112
3	GTCM-0	SC	16.4691	0.0839	15.068
		HWC	12.2389	0.0607	14.723
	GTCM-20	SC	16.3607	0.0723	11.794
		HWC	12.0793	0.0602	9.828

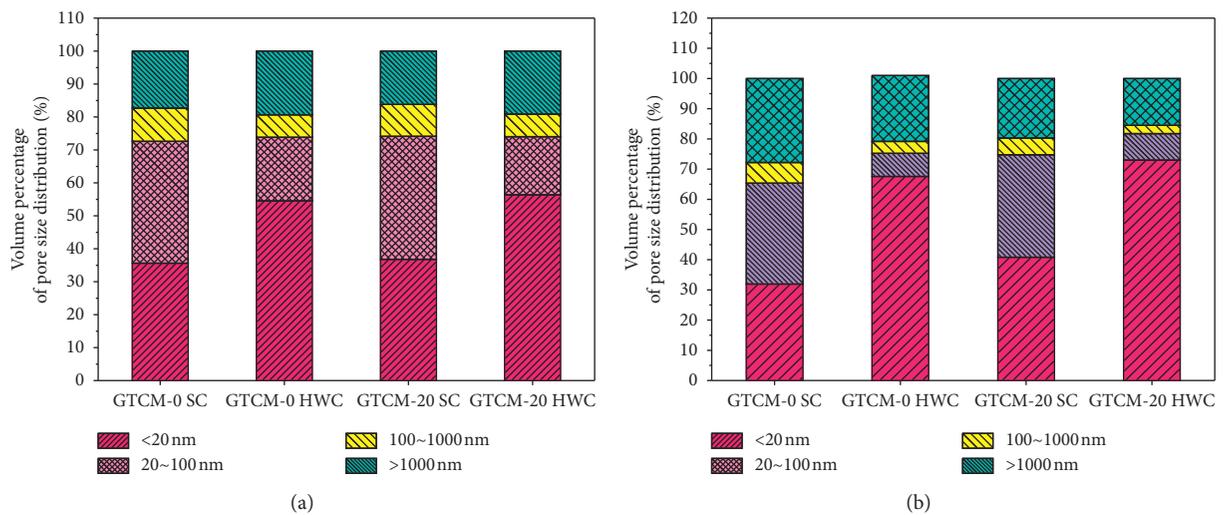


FIGURE 12: Pore volume percentage of GTCM-0 and GTCM-20 under SC and HWC methods: (a) 1 day and (b) 3 days.

methods, respectively; and the peak distribution appears in the range of 10 nm. The HWC method increases the pores in the range of <20 nm and 100–1000 nm but reduces the pore

volume within 20~100 nm and significantly increases the pore volume >1000 nm. For GTCM-0, a surge in the amount of Aft after hot-water curing for 1 day results in an increase

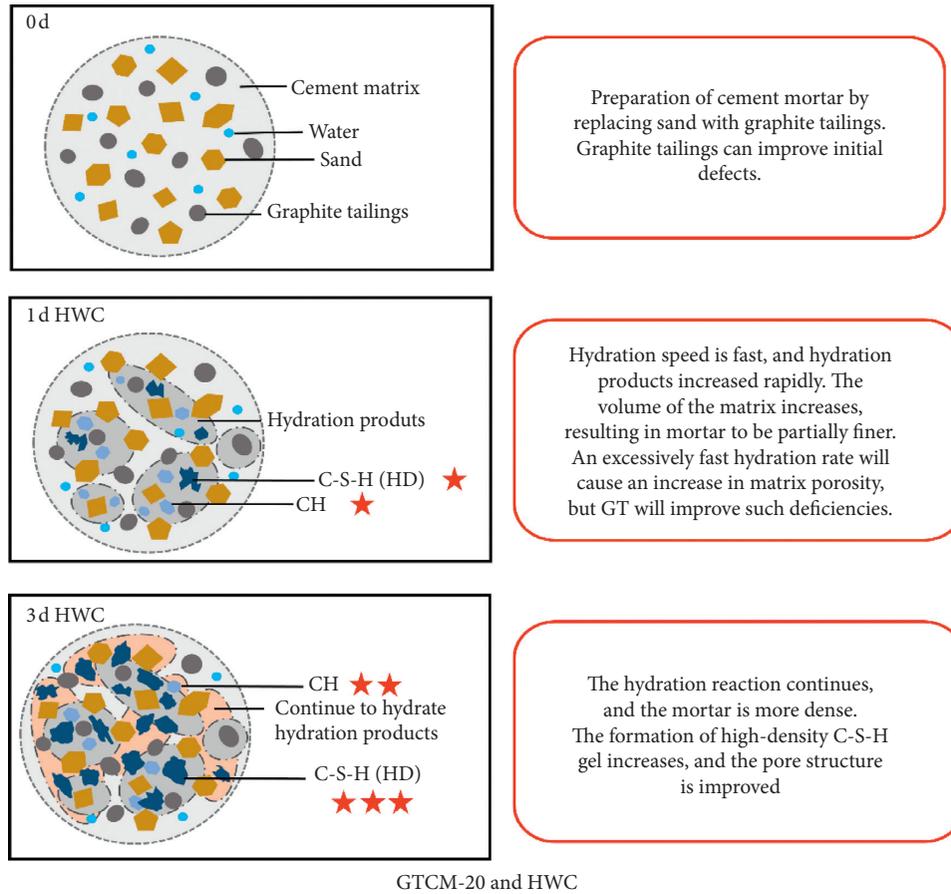


FIGURE 13: Combined effect mechanism diagram of the GT and HWC method on the early structure and performance of cement mortar.

in pores below 20 nm, whereas for CTCM-20, the change is due to the formation of high-density C-S-H. One-day hot-water curing causes the cement-based material to rapidly hydrate, which leads to early cracking, but the early cracking is compensated for due to the volume increase of the 20 nm pores and the production of C-S-H gel with an increased amount of Ca/Si or Aft. The mechanical properties are ultimately improved despite the shortcomings, and the incorporation of GT promotes a reasonable distribution of the pore structure. However, after one day of hot-water curing conditions, this promotion or increase in GT activity is not sufficient due to the short curing time, so there is no substantial change in the pore structure of GTCM-20 as a result of the HWC method. (2) The porosity of GTCM after 3-day curing is less than that of 1-day curing. At this time, the improvement due to the GT on the pore structure is highlighted. On the one hand, due to the increase of CH and low-density C-S-H gel during the SC method, the main peak position of the pore structure distribution curve of GTCM-20 is 50.4 nm smaller than the main peak position of GTCM-0 (50.6 nm). However, under SC conditions, the incorporation of GT also reduces the porosity (0.2% loss) and increases the pore size volume fraction with size <20 nm and has a significant effect on improving >1000 nm pore distribution. Due to the sufficient curing time, hot-water curing conditions are very helpful for the compactness of the

materials. For GTCM-0, the hot-water curing conditions increase the volume fraction of pores within 20 nm and decrease the pore volume ratio beyond 1000 nm by increasing the content of CH and  $\text{CaCO}_3$ , while the changes in GTCM-20 are due to the synergistic improvement of the amount of CH,  $\text{CaCO}_3$ , and high-density C-S-H. Finally, the most reasonable pore structure distribution can be obtained by the combined effect of a GT content of 20% and the HWC method.

**3.3. Mechanism of Combining GT and Curing Methods on the Early Performance.** Based on the material characterization results of the GTCM under the comprehensive effect of the GT and HWC method, the mechanism of the combined effects is shown in Figure 13. The particle size of graphite tailings is smaller than that of sand in Figure 3, so graphite tailings and sand can form reasonable particle gradation and reduce the gaps in cement mortar. The activity of graphite tailings is derived from a crystalline compound of calcium oxide and magnesium oxide, but the total composition of the two is only 17.88% in Table 2. Larger particles of graphite tailings have a large surface area and act as a support for aggregates. Graphite tailings are less than  $60 \mu\text{m}$  particles which only account for 24% in Figure 3, and there are still few active materials. The overall activity of graphite tailings from small particles is not very high, but after proper hot-

water curing which promotes hydration, graphite tailings can increase the strength of mortar. Therefore, the mechanism of graphite tailings improving mortar strength is as follows.

$3\text{CaO}\cdot\text{SiO}_2$  ( $\text{C}_3\text{S}$ ) and  $2\text{CaO}\cdot\text{SiO}_2$  ( $\text{C}_2\text{S}$ ) in cement react with water to form C-S-H and CH. The crystalline compound of calcium oxide and magnesium oxide in graphite tailings smaller than  $60\ \mu\text{m}$  react with water to produce a weakly alkaline compound. Alkali substances further promote the reaction between silicate and calcium ions in the mortar to form C-S-H [41, 42]. However, the promotion of graphite tailings on hydration reaction is limited. Graphite tailings are finer particles. A proper amount (20%–30%) of graphite tailings and sand can be used as aggregate to form reasonable gradation so that graphite tailings can increase the strength of mortar. If hot-water curing is used, it will not only accelerate the hydration reaction of cement but also accelerate the dissolution and reaction of active substances in graphite tailings, thereby improving the C-S-H gel morphology. So, the combination of the HWC method and GT, which is feasible, improves the strength of the cement mortar.

These curing methods could be applied when posttension construction member is made on-site, especially combined curing that is standard curing first and then hot-water curing. Standard curing allows the member to reach certain strength, and then hot-water curing allows the member to quickly reach design strength. Such two-stage curing reduces the prestress loss of the member because reinforcement and concrete become a whole as a result of concrete reaching certain strength. These curing methods could still be used in prefabricated and prestressed members in the factory.

It is worth noting that the service environment of the building materials in a cold area or coastal areas involves salt or freeze-thaw or coupling state, so the influence of the GT and curing methods on the early durability of cement-based materials needs further analysis to prepare early construction materials with synergistic development of mechanical properties and durability.

#### 4. Conclusions

This paper investigated the comprehensive properties and material characterization of GTCM during the combined effect of GT and curing methods, and the following conclusions were drawn:

- (1) The combined effect of the GT and HWC method increased the flexural strength and compressive strength of cement mortar which has an important impact on special engineering and rapid repair of structures.
- (2) The combined effect of the GT and HWC method improved the material characteristics of the cement-based materials at the early stage and provided substantial benefits, especially regarding the amount of hydration products, such as CH and high-density

C-S-H gel, the pore structure distribution, and the content of the main functional groups.

- (3) The comprehensive influence mechanism of the GT and HWC methods was illustrated in the presented model, and the optimal GT incorporation and optimal curing methods were quantitatively analyzed by the constructed equation. In summary, the results show that when the GT level is 20% and the HWC method is used, cement-based materials with excellent early performance can be prepared.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Disclosure

Hongbo Liu and Ben Li are the co-first authors.

#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Authors' Contributions

Hongbo Liu and Ben Li contributed equally to this work.

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