Effects of graphene oxide on early-age hydration and electrical resistivity of Portland cement paste

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Abstract: The effects of graphene oxide (GO) on the early-age hydration process and mechanical properties of Portland cement paste were experimentally investigated in this study. Based on an isothermal calorimeter measurement, the hydration rate of cement was observed to increase with the increase of GO content by nucleation effect. On the other hand, the electrical resistivity development of GO-cement paste was monitored using a non-contact electrical resistivity device. The result showed that electrical the resistivity of GO-cement paste was evidently higher than that of plain cement paste. However, cement paste with excessive amounts of GO exhibited a decreased electrical resistivity due to the massive ion diffusion caused by GO. Compared to plain cement paste, the GO-cement paste exhibited obviously higher compressive and flexural strengths, but the enhancements in compressive strength began to decline when the GO amount was greater than 0.04%. The microstructure characterization indicated that GO can apparently densify the cement pastes with less

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porosity and hydrates networking, which is consistent with the results of hydration acceleration and strength enhancement.

Keywords: Graphene oxide (GO), Hydration heat, Electrical resistivity, Mechanical strength, Microstructure

1. Introduction

Recent advances in nanotechnology have produced nanosized materials that have been used to improve mechanical properties and durability of cementitious materials, such as hindering the initiation and propagation of microcrack during the outset [1-3]. For example, nanosilica exhibits a spherical shape (low-aspect-ratio) with diameter less than 30 nm associated with a large specific surface area to accelerate cement hydration [4]. The enhanced static and impact mechanical properties by nanosilica and nanolimestone are generally attributed to two pozzolanic effect and nucleation effect [5,6]. In contrast to the spherical shape of nanoparticles, carbon nanotube (CNT) is regarded as a one-dimensional tubes (high-aspect-ratio). With the concurrent benefits of high aspect ratio and excellent mechanical performances, CNT has been found to greatly improve the elastic modulus and mechanical strengths of cement composites [7-9]. Moreover, the CNT can also accelerate the hydration reaction of the C_3S in Portland cement [10-11]. However, the incorporation of CNT in cement composites has proven to be rather complex, which are generally attributed to the poor dispersion of CNT [12]. As a two-dimensional nanosheet, graphene oxide (GO) is mono-layer of sp^2 -hybridized carbon atoms derived from a mixture of carboxyl, hydroxyl, and epoxy functionalities [13,14]. GO can be easily acquired from natural

46 graphite flakes (an inexpensive source) by strong oxidation and subsequent
47 exfoliation. The excellent mechanical properties of GO combined with its acceptable
48 dispersibility in water solution and affordable source make it a promising material to
49 enhance mechanical properties of cement composites [15-16]. It has been reported
50 that carboxyl acid groups can react with calcium silicate hydrate (C-S-H) to form
51 strong covalent bonds, thereby notably improving mechanical properties of
52 GO-cement composites [17,18]. Moreover, It shows that GO acts as an accelerator for
53 cement hydration by the nucleation effect, and also has physical filler effects to fill the
54 pores between cement grains to reduce permeability and densify the microstructure of
55 cement-based materials [19,20].

56 Isothermal calorimetry has been frequently used to measure the cement hydration,
57 which provides continuous measurements and is a convenient method to study the
58 early phase of hydration where the heat rate is relatively high [21,22]. Similar to
59 cement hydration heat characterization by the isothermal calorimetry measurements,
60 the development of electrical resistivity can also indicate the hydration process, which
61 relies on solid hydration products and ionic diffusions through water-filled pores in
62 cement composites [23,24]. The factors influencing the electrical resistivity of
63 cementitious materials are mainly controlled by microstructure and porous solution
64 conductivity. A non-contact electrical resistivity method was developed to measure
65 the development of resistivity of concrete mixtures [25,26]. The effects of cement
66 type, water/cement ratio, alkali content, superplasticizer selection, and blended
67 cement on the hydration process of cement composites were investigated using this

non-contact electrical resistivity measurement [27-31]. In this study, the effects of GO on the early-age hydration process mechanical properties of cement paste were investigated. The cement hydration process at the early-age was quantitatively measured by thermometric TAM air and non-contact electrical resistivity measurement, respectively. The mechanical properties of GO-cement paste were also evaluated to determine the degree of enhancements by GO. Moreover, the microstructures of GO-cement pastes were characterized to explore relationships between strength development and porosity and hydration in cement pastes.

2. Materials and methods

2.1. Raw materials

Portland cement was phrased from Cement Australia, West Footscray, and conformed to the requirements of Type I Normal Cement, as defined by the ASTM C150. The chemical compositions of the cement are shown in Table 1. Graphene oxide (GO) was obtained from Graphenea Inc., Spain, and the elemental properties are shown in Table 2. The transmission electron microscopy (TEM) image of 2D structure of GO is shown in Fig. 1. The GO solution from Graphenea was diluted with the mixing design required water by ultrasonication treatment. The ultrasonication was conducted by a Sonics Vibra-Cell vcx-500 ultrasonic processor from Vibra-Cell-Sonics & Materials, Inc. with energy of 40,000 Joules, amplitude of 80% and pulse of 4 seconds to improve the dispersion of GO in solution. After ultrasonication, the dispersed GO solutions were analyzed using UV-vis spectroscopy (UV-1800 Shimadzu Spectrophotometers). The UV-vis spectra was measured at 0 and 10 minutes

ultrasonication, in the wavelength range from 220 to 1100 nm. As observed in Fig. 2, the ultrasonication slightly enhanced the dispersion of GO in solution [32,33]. The tricalcium silicate (C_3S) was provided by the Mineral Research Processing company (Meyzieu France) to investigate effect of GO on C_3S (the major compound in Portland cement) hydration, and the chemical composition of C_3S is shown in Table 3.

2.2. Sample preparation

Cement paste with a constant water to cement ratio of 0.4 was prepared. Different amounts of GO were incorporated in cement psate as 0.02, 0.04, 0.06, and 0.08% by weight of cement to study effect of GO content on early-age properties of GO-cement paste. 0.02% GO C_3S paste and plain C_3S paste with a water to C_3S ratio of 0.4 were also prepared. The plain cement paste without GO served as the reference sample. A high-speed shear mixer (CTE Model 7000) was employed for sample mixing. The mixing procedure adopted was similar to ASTM C1738-11: firstly, add the correct amount of ultrasonicated GO solution dispersed in tap water into a mixing container and premix this solution at low speed of 100-200 revolutions per minute (rpm) for 15 seconds to homogenize it; secondly, add cement or C_3S into the mixing container within 30 seconds, and operate the mixer at a preset speed (4,000 rpm) for 60 seconds, then stop the mixer for 30 seconds; thirdly operate the mixer agin at a preset speed (12,000 rpm) for 30 seconds, then stop the mixer for 15 seconds and start the mixer at the same speed for an additional 30 secends. The fresh cement psate was used for isothermal calorimetry and electrical resistivity measurements. For the mechanical tests, the cement pastes were cast, compacted, and placed in a moist storage room (20

±2 °C) for 28 days to measure compressive and flexural strengths. The compressive strength measurement was conducted using cement paste cylinder of 25 mm (diameter) ×50 mm (height), and the flexural strength measurement was examined using non-notched beam of 140 mm (length) ×30 mm (width) ×15 mm (depth). At least three duplicate samples were tested for mechanical strengths measurement to ensure reproducibility of test results.

2.3. Thermometric TAM air

The effect of GO on the hydration heat of cement and C₃S pastes at early-age were evaluated according to the ASTM C 1679 by thermometric TAM air. In isothermal conduction calorimetry, the heat of hydration of cement is directly measured by monitoring the heat flow of the sample when both the sample and the surrounding environment are maintained at approximately isothermal conditions. A temperature of 25 °C was selected to simulate the standard curing condition. The isothermal calorimeter was conditioned at 25 °C for a day before real measurements, and the amplifier range was set at 600 mW. After the mixing, a paste sample of approximate 5.0 g was transferred into a sample ampoule of thermometric TAM. After the cementitious materials had been in contact with water for about 30 min, the calorimeter began to record heat. Thus, the heat generated initially during mixing and preparation was not captured. The heat generated from the hydration was monitored every minute for 48 hours and the measurement was normalized by sample mass.

2.4. Non-contact electrical resistivity measurement

The electrical resistivity was measured by a non-contact electrical resistivity

134 measurement device (Cement and Concrete Resistivity-III) as shown in Fig. 3(a). The
135 samples were cast into ring-shaped molds (1.67L) of dimensions 770 mm (perimeter)
136 $\times$ 55 mm (height) $\times$ 42 mm (width) including a cover for preventing water evaporation
137 during the test period. Data acquisition occurred at 5 seconds intervals over 24 hours.
138 As shown in Fig. 3(b), the incorporation of 0.01% GO (by weight of water) led to a
139 notable decrease in the electrical resistivity of tap water. This probaly is attributed to
140 the massive ion diffusions in the solution caused by the GO containing carboxylic
141 acid groups [14,34].

142 2.5. Mechanical test

143 The mechanical experiments on GO-cement pasts cylinder and non-notched beam
144 samples were performed to evaluate the compressive and flexural strengths. The
145 mechanical strengths of cement paste samples were measured after 28 days standard
146 curing in accordance with ASTM C109 and ASTM C348, respectively. Both the
147 compression and three-point bending tests were performed in the Concrete Structures
148 Laboratory at Monash University, Australia. Compressive strength was conducted
149 using a Shimadzu Universal testing machine (AG-X 300 kN) with a displacement
150 rate of 0.5 mm/min. Flexural strength was examined using an Instron Universal
151 testing machine (33R4204) with a displacement rate of 0.05 mm/min and a span
152 length of 110 mm.

153 2.6. Microstructure characterization

154 Microstructure characterization of cement paste incorporating GO was carried out
155 using a scanning electron microscope (SEM) technique of JEOL 7001F FEG with

high resolution at the Melbourne Centre for Nanofabrication, Australia. This device was equipped with a cold field emission electron gun operating at 15 kV. To examine the internal microstructure of GO-cement paste with crashed pieces of hardened samples obtained after electrical resistivity measurement and soaked in acetone to stop hydration. The sample surface was sputter coated with a thin layer (1.0 nm) of Pt/Pd prior to SEM test.

3. Results and discussion

3.1. Rate of hydration heat development

The rate of hydration heat of GO-C₃S pastes and GO-cement pastes are shown in Fig. 4. The GO-C₃S paste presented a slightly lower heat release rate and cumulative hydration heat than those of plain C₃S paste. The nucleation effect provided by GO is unlikely to accelerate the C₃S hydration. On the other hand, the GO-cement paste exhibited significantly higher hydration heat rate and cumulative heat than those of plain cement paste by the nucleation effect. With the amount of 0.02% GO, the dormant period (period of relatively low heat evolution) of cement paste was clearly reduced. The peaks of the heat flow shifted to the left and the magnitude was increased than that of plain cement paste. The increase in the heat release rate of GO-cement paste was more obvious at the second peak, which corresponds to the C₃A hydration [35,36]. Therefore, it implies that the nucleation effect provided by GO with large surface area is evidently more effective for the C₃A hydration rather than the C₃S hydration in Portland cement.

Fig. 5 shows the effect of GO content on the hydration heat of cement paste

178 containing 0.02, 0.04, 0.06 and 0.08% GO, respectively. It was found that the
179 hydration heat rate was proportionally increased with the increase of the GO amount.
180 As mentioned above, there were two effects of GO on the cement hydration, namely,
181 the nucleation effect and the dilution effect [37,38]. The nucleation effect is seem to
182 increase the heat release due to the hydration acceleration, whereas the dilution effect
183 is believed to decrease the heat release by dilution of major compounds in cement.
184 During the acceleratory period (before the first peak), the nucleation effect appeared
185 as a left shift of heat flow when the amount of GO was below 0.06%. When the
186 amount of GO was 0.08%, the dilution effect appeared as a right shift of heat release
187 flow. During the rapid reaction period (around the first and second peaks), with the
188 increase in GO content, there was a moderate increase in magnitude at the first peak
189 but a significant increase around the second peak. The second peak of heat flow
190 shifted to left, indicating that the hydration duration to reach the main peaks decrease
191 as the GO content increases.

192 From Fig. 6, it shows that the cumulative hydration heat release of GO-cement
193 paste generally increases with the amount of GO during 48-hour hydration. During
194 the first 8-hour hydration, the GO-cement paste with 0.08% GO exhibited lower
195 cumulative heat release than that of plain sample due to the dilution effect by large
196 amount of GO, whereas the other GO-cement pastes (incorporating 0.02 to 0.06% GO)
197 exhibited higher cumulative heat compared to reference sample. After 8-hour
198 hydration, the GO-cement pastes with GO developed significantly more hydration
199 heat than that of the plain sample due to the nucleation effect. The cement paste

incorporating GO amount of 0.08% exhibited higher accumulative hydration heat than those of samples with GO contents of 0.02 to 0.06% because the nucleation effect dominantly compensated the dilution effect in the late age. However, the increase in accumulative hydration heat by GO incorporation gradually diminished when the hydration time approached 48-hour. In comparison to the reference sample, the increases in cumulative hydration heat of the GO-cement pastes with different GO contents are 0.77J/g for 0.02% GO, 3.30J/g for 0.04% GO, 3.90J/g for 0.06% GO, and 11.46J/g for 0.08% GO, respectively.

3.2. Development of electrical resistivity

Based on the previous literatures [26,27,39,40], the electrical resistivity development during early-age hydration can be divided into four stages. The electrical resistivity developments of GO-cement pastes and plain sample with hydration time up to 24-hour are shown in Fig. 7(a). It was found that the GO-cements with different amounts of GO exhibited generally similar electrical resistivity development trends. The electrical resistivity development of GO-cement paste during the 24-hour hydration was approximately divided into 4 stages. For example, the hydration stages of plain cement paste can be shown as follows: In the first stage (I, dissolution), the electrical resistivity begins with a small decline corresponding to the dissolution of ions from cement into water and reaches the minimum point at around 0.92 hour hydration. In the second stage (II, setting), the electrical resistivity shows nearly constant development at a relative low rate and keeps this tendency until 4.3 hours hydration. The initial hydration products form, reducing the ion concentration and

222 allowing additional ions from cement particles to dissolve. In the third stage (III,
223 acceleration), the resistivity increases gradually due to the growth of hydration
224 products. This increase continues through the whole test period up to 10.3 hours
225 hydration. Between 10.3 and 13.3 hours hydration, there is a drop in the electrical
226 resistivity development because the transformation from AFt to AFm in this period
227 [41]. It should be noted that the GO-cement pastes presented different appearance
228 times of this transformation when different GO contents were incorporated. In the
229 fourth stage (IV, deceleration), the electrical resistivity continues to increase until
230 24-hour hydration. Based on the electrical resistivity developments, the hydration
231 stages of GO-cement pastes with different amount of GO are shown in Table 4.

232 Overall, the electrical resistivity development and characteristics and trends of
233 GO-cement pastes are consistent with the results in previous researches [23,24,29,30].

234 During the dissolution and setting stages, the electrical resistivity of GO-cement
235 generally increased due to the decrease of free water, which was caused by the high
236 adsorption capacity of GO with large surface areas, as shown in Fig. 7(b). With the
237 process of hydration, the increase in solid hydration products [20,42], and the
238 decrease of porosity tended to block the conduction path of ions in GO-cement paste,
239 thus increasing the electrical resistivity. However, between 10.3 and 13.3 hours
240 hydration, GO-cement pastes exhibited clear drops in electrical resistivity
241 development, which corresponded to the transformation of AFt to AFm. It can be
242 found that the GO content affect this transformation between AFt and AFm. During
243 the next hydration, the increase in electrical resistivity of GO-cement paste

progressively declined. After 24-hour hydration, the GO-cement paste with GO amounts of 0.06% and 0.08% exhibited even lower electrical resistivity than that of plain sample, which could be attributed to the increased ion diffusion caused by GO containing many carboxylic acid groups and similar results were also found in nano-modified composites, especially in the acceleration stage of hydration [43,44].

The electrical resistivity development rate of GO-cement paste with GO amounts from 0.01 to 0.08% is shown in Fig. 8(a). In the I stage, the electrical resistivity decreased due to the increase of ion concentration and the mobility of these ions. But when GO was added, the free water in the cement paste was reduced by the high water absorption, resulting in higher electrical resistivity compared to that in the reference sample. In the II stage, due to high dilution effect, a gel layer or membrane formed rapidly over the surfaces of the cement grains [40,41]. GO sheets provided nucleation sites to accelerate cement hydration, which also increased the electrical resistivity development. In the III stage, the hydration rate was increased significantly by GO, leading to rapid hardening [17,45]. In the IV stage, as the hydration continued, the hydrates form a thicker barrier that blocks the exposure of the solution to unhydrated cement particles. Then the ion diffusion controlled the development of the electrical resistivity. Therefore, GO-cement pastes exhibited relatively low development of electrical resistivity in comparison to reference sample. From Fig. 8(b), the electrical resistivity values after 24-hour hydration of GO-cement pastes incorporating GO contents of 0.01 and 0.02% were higher than that of reference sample. However, when the GO addition exceeds 0.04%, the increase in electrical

266 resistivity of GO-cement paste began to decline. For instance, the cement paste
267 incorporating 0.08% GO presented even lower electrical resistivity compared to plain
268 sample. The maximum electrical resistivity appeared in GO-cement paste with 0.02%
269 GO. These result implies that the optimal amount of GO for electrical resistivity is
270 0.02%. Therefore, the amounts of 0.02 and 0.04% GO seem more effective to
271 acceleration the cement hydration at the early-age. But the long-term electrical
272 resistivity developments and hydration process of GO-cement pastes are still worth
273 further investigation such as after 28-day curing.

274 *3.3. Mechanical strengths*

275 The effect of GO on the compressive and flexural strengths of GO-cement pastes with
276 the GO contents of 0.02, 0.04, 0.06 and 0.08% after 28-day standard curing were
277 displayed as shown in Fig. 9(a). The result shows that in comparison to the reference
278 sample the compressive strength of cement pastes incorporating GO of 0.02, 0.04,
279 0.06 and 0.08% was greatly enhanced by 19.1, 37.0, 46.6 and 46.8%, respectively.
280 The increase in compressive strength of GO-cement pastes could be due to the
281 hydration acceleration effect on the cement hydration kinetics, stimulating the growth
282 of hydration products. However, it clearly shows that compared to the plain cement
283 paste, the enhancement in compressive strength of GO-cement paste tended to decline
284 with the increase of GO dosage. Fig. 9 (b) shows that the GO obviously also enhanced
285 the flexural strength of cement pastes. For instance, with GO dosages of 0.02 and
286 0.04%, the increases in the flexural strength of cement paste relative to that of
287 reference sample are 4.5% and 14.2%, respectively. The maximum flexural strength

was achieved by GO dosage of 0.04%. The improvement in flexural strength could be due to the high specific surface area of GO, which improved the bond interface between GO and paste matrix. However, the flexural strength of cement paste was observed to decrease in comparison to reference sample when the GO dosage was greater than 0.04%. The factor which mitigated the improvement in mechanical strengths as the GO content increased was likely due to GO agglomeration, which affected flexural strength enhancement negatively, especially in the case of 0.08 % GO incorporation [3,46].

3.4. Microstructure characterization

The process of cement hydration results in a decrease in pore space and an increase in volume of solid hydrates, which accompanies hydration heat release and electrical resistivity development [45,46]. Therefore, there are intrinsic relationships among microstructure, hydration heat release and electrical resistivity development of cement paste. In this study, the microstructures of GO-cement pastes were analyzed by SEM. In cement paste, cement grains were separated after mixing with water. With increase in hydration, the solid cement particles begin to connect with each other. From Fig 10, the microstructure characterization shows that the GO-cement paste with 0.02% GO presented apparently fewer pores and more hydration product networking around the microcracks than the plain cement paste. Thus, the GO contributed to the more formation of hydration products in cement pastes. Furthermore, the accelerated hydration because of the GO incorporation led to denser microstructures and consequently higher electrical resistivity of GO-cement paste with optimal GO

310 content.

311 **4. Conclusions**

312 The effects of GO on the hydration processes and electrical resistivity of Portland
313 cement paste at early-age were investigated using isothermal calorimeter and
314 non-contacting resistivity measurements. Based on the experimental results, the
315 following conclusions can be drawn:

316 (1) With incorporation of GO, the dormant period of cement hydration was shortened,
317 and the hydration rate was accelerated by the nucleation effect. Among the major
318 compounds of cement, the GO can greatly increase the hydration rate of C_3A
319 rather than C_3S .

320 (2) The GO-cement pastes exhibited an increase in cumulative hydration heat than
321 the plain cement paste because of the acceleration effect. However, the dilution
322 effect slightly decreased the cement hydration process when large amount of GO
323 was added in cement paste during the dissolution stage.

324 (3) When GO was added into cement paste, the development of electrical resistivity
325 increased during the dissolution and setting stages because the free water was
326 reduced by the high adsorption of GO. During the acceleration stage, the
327 electrical resistivity exhibited evident increase due to the nucleation effect of GO.

328 (4) The enhancements in electrical resistivity of GO-cement pastes were decreased
329 because of the ion diffusion caused by the GO containing carboxylic acid groups
330 during the deceleration stages. The electrical resistivity of cement paste with 0.06
331 and 0.08% of GO amount was relatively lower than that of the plain sample.

(5) Compared to the plain cement paste, GO-cement pastes presented obviously denser microstructure and more hydration product networking around porous areas, which was consistent with the higher hydration heat release and the development rate of electrical resistivity in the early-age.

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457 **Tables**

458 [Table 1](#) Chemical composition of Portland cement (in percentage)

459 [Table 2](#) Elemental analysis of graphene oxide (<http://www.graphenea.com>)

460 [Table 3](#) Chemical composition of tricalcium silicate

461 [Table 4](#) Hydration stages of GO-cement pastes based on electric resistivity

462 development (hours)

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474 **Table 1** Chemical composition of Portland cement (in percentage)

Al ₂ O ₃	SiO ₂	CaO	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	SO ₃	Loss on ignition	Others
4.7	19.9	63.9	3.4	0.5	1.3	0.2	2.6	3.0	0.5

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494 [Table 2](http://www.graphenea.com) Elemental analysis of graphene oxide (<http://www.graphenea.com>)

Element	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
%	49~56	0~1	0~1	0~2	41~50

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514 [Table 3](#) Chemical composition of tricalcium silicate

Elements	Weight percentage (%)	Oxides	Weight percentage (%)
Ca	52.66	CaO	73.68
Si	12.36	SiO ₂	26.32
O	35.04		

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Table 4 Hydration stages of GO-cement pastes based on electric resistivity

development (hours)				
Mixes	Dissolution	Setting	Acceleration	Deceleration
Plain cement paste	0 ~ 0.92 h	0.92 ~ 4.3 h	4.3 ~ 13.3 h	After 13.3 h
0.01% GO-cement	0 ~ 1.1 h	1.1 ~ 4.3 h	4.3 ~ 13.1 h	After 13.1 h
0.02% GO-cement	0 ~ 0.8 h	0.8 ~ 3.9 h	3.9 ~ 11.7 h	After 11.7 h
0.04% GO-cement	0 ~ 0.9 h	0.9 ~ 4.2 h	4.2 ~ 12.6 h	After 12.6 h
0.06% GO-cement	0 ~ 0.9 h	0.9 ~ 4.3 h	4.3 ~ 12.7 h	After 12.7 h
0.08% GO-cement	0 ~ 1.1 h	1.1 ~ 4.3 h	4.3 ~ 13.7 h	After 13.7 h

Figures

[Fig. 1.](#) Transmission electron microscopy images of GO sheets

[Fig. 2.](#) Graphene oxide dilution solution and dispersion evaluation

[Fig. 3.](#) Electrical resistivity measurement and effect of GO on electrical resistivity of liquid phase: (a) GO solutions after ultrasonic treatment; (b) Ultraviolet-visible spectroscopy

[Fig. 3.](#) Electrical resistivity measurement and effect of GO on electrical resistivity of liquid phase: (a) Non-contact electrical resistivity apparatus; (b) Effect of GO on electrical resistivity

[Fig. 4.](#) Effect of GO on hydration heat of C₃S and cement pastes during 48-hour hydration: (a) Rate of heat hydration; (b) Total cumulative heat of hydration

[Fig. 5.](#) Effect of GO amounts on hydration heat rate of GO-cement paste during 48-hour hydration: (a) Rate of heat released during hydration; (b) Difference in rate of heat hydration

[Fig. 6.](#) Effect of GO on cumulative hydration heat of GO-cement pastes during 48-hour hydration: (a) Total cumulative heat of hydration; (b) Difference in cumulative heat

[Fig. 7.](#) Electrical resistivity development of GO-cement pastes during 24-hour hydration: (a) Electrical resistivity development; (b) Difference in resistivity development

[Fig. 8.](#) Development rate of electrical resistivity and final electrical resistivity of GO-cement pastes after 24-hour hydration: (a) Rate of electrical resistivity

561 development; (b) Electrical resistivity of GO-cement paste

562 [Fig. 9](#). Mechanical strengths of cement pastes with different GO after 28-day curing:

563 (a) Compressive strength; (b) Flexural strength

564 [Fig. 10](#). Microstructure of GO-cement paste and plain cement paste after 24 h

565 hydration: (a) Plain cement paste; (b) Local area of plain cement paste; (c)

566 GO-cement paste (0.02% GO); (d) Local area of GO-cement paste

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[Fig. 1.](#) Transmission electron microscopy images of GO sheets

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(a) GO solutions after ultrasonic treatment

(b) Ultraviolet-visible spectroscopy

Fig. 2. Graphene oxide dilution solution and dispersion evaluation

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(a) Non-contact electrical resistivity apparatus

(b) Effect of GO on electrical resistivity

Fig. 3. Electrical resistivity measurement and effect of GO on electrical resistivity of liquid phase

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(a) Rate of heat hydration

(b) Total cumulative heat of hydration

Fig. 4. Effect of GO on hydration heat of C_3S and cement pastes during 48-hour hydration

(a) Rate of heat released during hydration

(b) Difference in rate of heat hydration

Fig. 5. Effect of GO amounts on hydration heat rate of GO-cement paste during 48-hour hydration

(a) Total cumulative heat of hydration

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Fig. 6. Effect of GO on cumulative hydration heat of GO-cement pastes during 48-hour hydration

(a) Electrical resistivity development

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Fig. 7. Electrical resistivity development of GO-cement pastes during 24-hour hydration

(a) Rate of electrical resistivity development

(b) Electrical resistivity of GO-cement paste

Fig. 8. Development rate of electrical resistivity and final electrical resistivity of GO-cement pastes after 24-hour hydration

(a) Compressive strength

(b) Flexural strength

Fig. 9. Mechanical strengths of cement pastes with different GO after 28-day curing

(a) Plain cement paste (10 ×10 μm)

(b) Plain cement paste (10 ×10 μm)

(c) GO-cement paste (10 ×10 μm)

(d) GO-cement paste (10 ×10 μm)

Fig. 10. Microstructure of GO-cement paste (0.02%) and plain cement paste after 24-hour hydration