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Effect of Lamellar Inorganic Fillers on the Properties of Epoxy Emulsion Cement Mortar

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Abstract

Lamellar inorganic fillers have been used to improve the performance of polymer composites. In this paper, five kinds of lamellar inorganic fillers, including montmorillonite (MMT), mica, talc, glass flake (GF) and lamellar double hydroxide (LDH), were selected to modify epoxy emulsion cement mortar (EECM). The research evaluated the effects of the structure characteristics of lamellar fillers on the mechanical properties, water absorption and chloride ion permeability resistance of EECM, with comparison to granular ground calcium carbonate (GCC). Results indicated that lamellar fillers had no obvious superiority than GCC in the mechanical strength of EECM, even MMT caused the decline of the mechanical strength. However, lamellar fillers had improved the chloride ion permeability resistance of EECM compared with GCC, and they had the similar effect on reducing of water absorption except MMT. Although the low aspect ratio (AR) of the lamellar fillers benefited the increase of the strength and water resistance of EECM, the lamellar fillers with higher AR could improve the chloride ion permeability resistance of EECM more efficiently.

Keywords: lamellar inorganic fillers, epoxy emulsion cement mortar, aspect ratio, chloride diffusion coefficient

1 Introduction

As a traditional building repair material, cement mortar still occupies an important position in the architectural field in the 21st century (Biernacki et al. 2017). Ordinary Portland cement mortar has porous structure (Chen et al. 2017), poor toughness and durability (Zhang et al. 2017). Some ions, such as Cl^- and SO_4^{2-}, easily penetrate cement mortar and led to rusting of the reinforced concrete structures (Alhozaimy et al. 2016; Conciatori et al. 2010; Abdalkader et al. 2017), therefore, the resistance to chloride ion permeability as well as the mechanical properties of cement mortar in coastal engineering is required to improve.

Studies indicated that the mechanical properties and resistance to chloride permeability of cement mortar could be improved by polymer materials (Wang et al. 2005; Zhong 2003), especially epoxy resin with excellent corrosion resistance, bonding and mechanical strength (Zhang and Yan 2017). However, the epoxy resin has a very limited effect on improving the toughness of ordinary cement mortar and concrete due to the poor resistance to crack propagation of cured epoxy resin. Moreover, some bubbles was introduced during the mixing process which weakens the improvement effect on the penetration resistance and strength of cement mortar (Afzal et al. 2016; Li et al. 2015). Therefore, there are much research work to improve the performance of epoxy emulsion cement mortar (EECM).

Inorganic filler was widely used to modify polymer composites (Yang et al. 2003; He and Gao 2015; Si et al. 2016; Katiyar et al. 2016; Meng et al. 2015), due to the high efficiency in improving the mechanical properties, especially the anti-permeability of polymer cement

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mortar (Kim and Kim 2014; Rahman and Islam 2013; Zuo et al. 2017; Leung et al. 2008; Alonge et al. 2017; Aguayo et al. 2014). The anti-permeability of EECM could be improved by adding some inorganic fillers which with volcanic ash effect, ion adsorption, ion exchange and micro-aggregate filling effect. Kim and Kim (2014) found that nitrite-type hydrocalumite enhanced the resistance to chloride penetration and carbonation resistance of epoxy modified mortar and obtained an excellent corrosion inhibition performance. Rahman and Islam (2013) added rice husk ash into epoxy mortar and epoxy concrete and found the contribution of rice husk ash to the resistance to chloride diffusion and mechanical properties. Zuo et al. (2017) introduced glass flakes into EECM and found that glass flakes with proper size had good effect on the resistance to chloride permeability, water resistance and flexural strength. Leung et al. (2008) used quaternary ammonium modified montmorillonite, octadecylamine modified montmorillonite and epoxy resin to prepare polymer/organoclay nanocomposites and found that nanocomposites could more effectively inhibit chloride ions and water vapor from entering concrete than neat polymers. By addition of metakaolin and epoxy resin, the water absorption and chloride permeability of the cement-based composite prepared by Alonge et al. (2017) were reduced significantly, compared with control group. Aguayo et al. (2014) studied the influence of limestone, fly ash and metakaolin on concrete, and found the improvement effect of metakaolin on the strength and the resistance to chloride transport of concrete was better than limestone and fly ash. However, so far, there were no comparison about the effect of these inorganic fillers on the performance of EECM, and the relationship between the morphology of fillers and the strength of EECM, especially the resistance to chloride penetration, had not been discussed in detail.

Although, the aspect ratio and morphology of inorganic fillers affected the performance of polymer composites (Depolo and Baird 2009; He et al. 2017; Gahleitner et al. 1994; Švehlová and Polouček 1994; Mitsuishi 1997), the study on the properties of polymer cement mortar was relatively limited. Previous scholars studied the performances of cement mortar affected by MMT, mica, talc, GF and LDH (Zuo et al. 2017; Piqué et al. 2013; Tugrul et al. 2015; Vlahovic et al. 2011; Xu et al. 2009), however, which were not comprehensive and lack of theoretical guidance. Theoretically, lamellar fillers have a advantage in channel plugging of composites. In the present study, MMT, mica, talc, GF and LDH with lamellar structure were selected to modify EECM, respectively. The effects of the structure and morphology of the lamellar fillers on the strength and anti-permeability of EECM were discussed. The microstructure and action mechanism of fillers were observed by SEM. In addition, the granular GCC was used to modify EECM, as a comparison with the lamellar fillers. This paper provided some regular summaries and theoretical support for the influence of inorganic fillers on the performance of EECM.

2 Experimental

2.1 Materials

The ordinary Portland cement (P.O. 42.5R) was supplied by Yingde Conch Cement Co., Ltd. in China, the sand was purchased from Xiamen ISO Standard Sand Co., Ltd. in China. The waterborne epoxy resin (H123A) and the hardener (H123B) were purchased from Shanghai Hanzhong Chemical Industry Co., Ltd. in China. Talc was provided by Shanghai Yuanjiang Chemical Co., Ltd. (Shanghai, China), mica was purchased from Yufeng Powder Material Co., Ltd. in China, LDH was the product of Hunan Shaoyang Tiantang Auxiliaries Chemical Co., Ltd. Ground calcium carbonate (GCC) was purchased from Jiangxi Gaofeng Calcium Carbonate Co., Ltd. Montmorillonite (MMT) was purchased from Lingshou Hengchang Minerals Processing Factory, glass flake (GF) was provided by Hejian Chaohui Glass Flake Co., Ltd. in China. The chemical compositions of fillers were characterized by X-ray fluorescence spectrometer (S4-Explorer) and shown in Table 1. The water was tap water.

Aspect ratio (AR) is an important parameter of filler which affects the properties of the composites. And it is described as the ratio of the filler surface diameter to the thickness of a lamellar structure (He et al. 2017; Xia and Kopsky 2017; Sheng et al. 2004). At present, there is no standard test method for AR, and general analysis is performed by observing the scanning electron microscope (SEM), atomic force microscopy (AFM) and transmission electron microscope (TEM) photographs (He et al. 2017; Beckett et al. 1997; Tumolva et al. 2012; Veghte and Freedman 2014). In this paper, the average diameter and thickness of fillers are measured by SEM, the AR values are calculated and given in Table 2. The AR-7, AR-24, AR-110, AR-300 and AR-600 are the AR of LDH, GF, Mica, MMT and Talc, respectively. There is no AR value of GCC due to its irregular morphology.

2.2 Preparation of specimens

The waterborne epoxy resin and hardener were first mixed with the ratio of 1:1.3, and after adding water, the blends were stirred thoroughly to form homogeneous emulsion. Meanwhile, the filler (MMT, Mica, Talc, GF, LDH, GCC), sand and cement were introduced into a mortar mixer (JJ-5, Wuxi, China) and mixed uniformly. Then, the mixed epoxy emulsion was introduced into the mortar mixer and stirred well, and the obtained slurry was poured into different moulds. After 24 h, the filler

Table 1 Chemical composition of inorganic fillers.

Fillers	Chemical composition, wt%									
	SiO_2	Al_2O_3	MgO	CaO	Fe_2O_3	K_2O	Na_2O	TiO_2	SO_3	P_2O_5	ZnO
MMT	75.7	14.8	3.71	3.02	1.53	0.43	0.38	0.11	–	–	0.013
Mica	29.2	0.15	53.68	16.3	0.352	0.024	–	–	–	0.13	–
Talc	42.2	0.43	39.56	17.2	0.268	–	–	–	–	0.089	–
GF	64.6	6.68	3.47	10.3	0.512	1.07	12.4	0.054	0.16	0.079	–
LDH	–	28.8	33.1	2.95	0.056	0.38	15.1	–	3	–	0.042
GCC	0.35	–	31.5	67.6	0.12	–	–	–	–	–	–

Table 2 Characteristics of the used fillers.

Samples	LDH	GF	Mica	MMT	Talc
Average diameter (um)	~0.1	~48	~11	~3	~12
Average thickness (um)	~0.015	~2	~0.1	~0.01	~0.02
Aspect ratio (AR)	~7	~24	~110	~300	~600

Table 3 Mix weight proportion of modified EECM.

Samples	Polymer-cement ratio	Water-cement ratio	Sand-cement ratio	Filler-cement ratio (%)
Control	0.15	0.4	3:1	–
Modified EECM	0.15	0.4	3:1	5
	0.15	0.4	3:1	10
	0.15	0.4	3:1	15
	0.15	0.4	3:1	20

modified EECM specimens were removed from moulds and moved to a wet curing box (temperature = 20 ± 3 °C, relative humidity ≥ 80%) for 2 days. And then, the specimens were immersed in water for 5 days, and finally moved to a dry curing box (temperature = 20 ± 3 °C, relative humidity ≥ 60%) for 21 days (Chinese Standard 2001). The mix proportion of modified EECM by weight was shown in Table 3.

2.3 Mechanical properties test

In accordance with the China standard DL/T 5126-2001 (Chinese Standard 2001), the flexural strength and compressive strength test for modified EECM was executed using a constant loading cement bending compression testing machine and the loading rates were 50 ± 10 N/s and 2400 ± 200 N/s, respectively. After maintenance for 28 days, three prism specimens of 160 × 40 × 40 mm^3 were used and the average value was adopted.

2.4 Water absorption test

Curing for 28 days, the specimens were transferred to a drying box (temperature = 80 ± 2 °C) and dried for 48 h, then cooled to room temperature and weigh the specimens (G_0) quickly. After that, the specimens were immersed in water (temperature = 20 ± 2 °C) for 48 h, then transferred from water, and weigh the specimens (G_1) after wiping off the surface water. Water absorption was calculated according to the China standard DL/T 5126-2001 (Chinese Standard Chinese Standard. 2001), by the following equation:

$$W_A = \frac{G_1 - G_0}{G_0} \times 100\% \tag{1}$$

where W_A is the water absorption (%); G_0 is the weight of the specimen after drying (g); G_1 is the weight of the specimen after water absorption (g).

2.5 Rapid Chloride Migration (RCM) Test

The curing date was 28 days, to determine the chloride permeability resistance, three Φ 100 mm × 50 mm cylindrical specimens were used. The specimens were transferred to a vacuum vessel with a pressure of 10–50 mbar and applied for 3 h. After that, the saturated limewater was poured into vacuum vessel to immerse the specimens, with the vacuum-pump still running for 1 h. Then, the samples were immersed in saturated limewater with atmospheric pressure for 18 ± 2 h. After the RCM test set-up was connected, 10% NaCl solution was injected into the cathode test sink and 0.3 M NaOH solution was filled into the anodic rubber sleeve. The initial voltage was 30 V, the test voltage and the test time were determined by the initial current (Elfmarkova et al. 2015). After the RCM test, the specimens were removed from rubber sleeve and split, then sprayed with 0.1 M $AgNO_3$ solution to determine the penetration depth of chloride (Fan et al. 2014). The D_{RCM} coefficient was calculated by the following equation (Chinese Standard 2009):

$$D_{RCM} = \frac{0.0239 \times (273 + T)L}{(U - 2)t} \times \left(X_d - 0.0238\sqrt{\frac{(273 + T)LX_d}{U - 2}} \right) \quad (2)$$

where D_{RCM} is the non-steady state chloride ion migration coefficient with an accurace of 0.1×10^{-12} m^2/s; U is the absolute value of the applied voltage (V); T is the average value of the initial and end temperature in the anode solution (°C); L is the specimen thickness (mm) with an accurace of 0.1 mm; X_d is the average value of the chloride ion penetration depth (mm) with an accurace of 0.1 mm; t is the test time (h).

2.6 Scanning Electron Microscope (SEM) Observation

Prior to observing, these five kinds of fillers and the corresponding fractured pieces of mortar specimens (curing for 28 days) were sprayed with gold for 60 s. Then, the test samples were observed and analyzed by SEM (SU-70, Hitachi Limited).

3 Results and Discussion

3.1 Mechanical Properties

The flexural strength of EECM modified by different fillers is shown in Fig. 1. As shown in Fig. 1a, the flexural strength of GCC modified EECM has the highest value. Compared with control group without filler, the flexural strength has a great improvement of 27.3% with the GCC content of 15–20 wt%. Li et al. (2015) also found that the flexural strength of epoxy resin mortar was improved with increasing GCC amount. The size of GCC is between the sand and cement and it has a significant "bridge effect" in EECM, which reduces the brittle failure of EECM. Meanwhile, the flexural strength of MMT modified EECM is lowest, and even lower than the control group. It may be the reason that the strong water absorption of MMT (Yu et al. 2013), which causes the decline in the fluidity of EECM, as a result the cement hydration process is hindered and can not form a complete organic–inorganic crosslinking structure with epoxy resin. Four fillers with lamellar structure, mica, talc, GF and LDH, all make the flexural strength of EECM increased. It can be seen that the surface characteristics of filler significantly affect the strength of composites, but the filler morphology has little effect on the strength, and the lamellar filler has no obvious advantage in improving the flexural strength compared with the granular filler.

The studies about the influence of filler aspect ratio on the mechanical properties of polymer composite showed that the aspect ratio of filler usually affected its dispersion and interfacial bonding in composite material, and thus influenced the strength of composite (Depolo and Baird 2009; He et al. 2017; Gahleitner et al. 1994; Švehlová and Polouček 1994; Mitsuishi 1997). Figure 1b reveals the relationship between the aspect ratio of filler and the flexural strength of EECM. The flexural strength of EECM is enhanced by adding lamellar filler, and the bridge effect of filler in EECM prevents crack extension and dissipates fracture energy. On the whole, the flexural strength of modified EECM increases first and then decreases with the increase of aspect ratio, the aspect ratio of LDH is the smallest and the aspect ratio of talc is the largest among these five types of lamellar fillers. Combining the fact that the thickness of talc, MMT and LDH is less than 20 nm, while the thickness of mica and GF is over 0.1 μm (Table 2), it can be concluded that the lamellar filler with larger thickness has greater contribution to the flexural strength of EECM. Although the aspect ratio of MMT is not the largest, the flexural strength of MMT modified EECM is the lowest due to its strong water absorption.

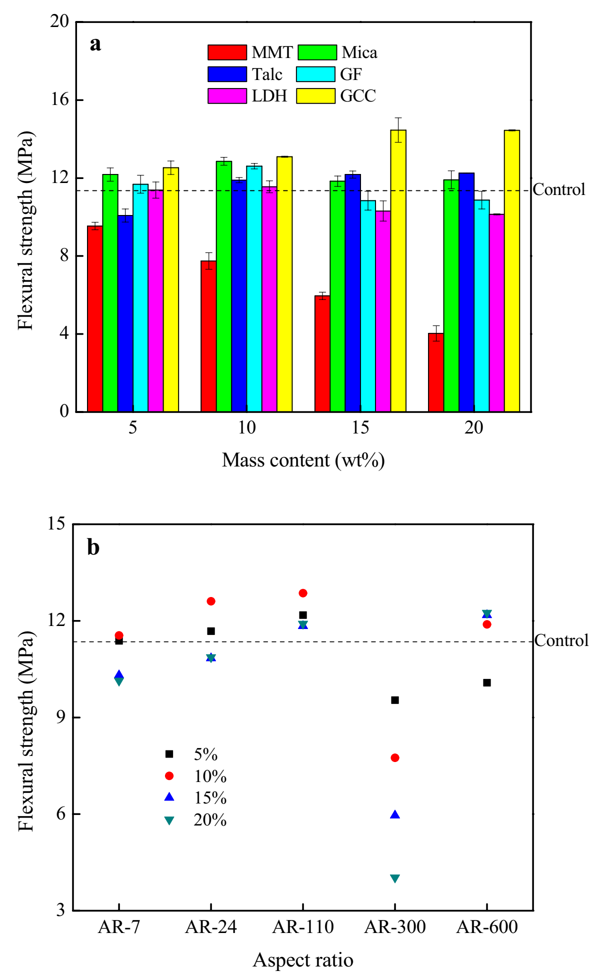

Fig. 1 Flexural strength of the modified EECM with different fillers. **a** Filler contents; **b** aspect ratios of fillers.

Figure 2a shows the compressive strength of EECM modified by different fillers. By adding fillers, the compressive strength of modified EECM is not improved significantly, even with the filler content of up to 20%, and only the EECM with GCC has relatively higher values. This may be due to larger modulus and better micro-aggregate filling effect of GCC. Previous study also indicated that the physical filling effect of aggregate micro fines may improve the performance of cement concrete (Wang et al. 2013). However, the compressive strength of EECM got decreased with the increase of MMT amount. The main reason is that the strong water absorption of MMT reduces the hydration degree of cement, and results in the decrease in the compressive strength of EECM. Figure 2b depicts the relationship between the aspect ratio of lamellar filler and the compressive strength of modified EECM. With improving the aspect ratio of lamellar filler, the compressive strength of modified EECM increases first and then decreases, which is similar to the change tendency of the flexural strength. Meanwhile, the EECM modified by talc, MMT and LDH has a lower compressive strength, which may be related to the low thickness of talc, MMT and LDH.

The toughness of mortar is an important indicator of anti-cracking performance. In the field of mortar, the ratio of flexural and compressive strength (f_b/f_c) is usually used to evaluate fracture toughness (Wang et al. 2005; Li et al. 2015; Luo et al. 2013), the greater f_b/f_c value represents the better toughness of mortar. Figure 3a indicates the influence of different fillers on f_b/f_c values of modified EECM. With the rise of GCC contents, the promotion of the f_b/f_c values of EECM can be observed. It has been reported that rigid particles provide stress conditions for the shear yield of the matrix mainly by changing the local stress state (Wetzel et al. 2006; Lee and Yee 2001). The f_b/f_c values of EECM with MMT are lower than EECM with other fillers regardless of any content. Although MMT has micro-aggregate filling effect in mortar, its greater

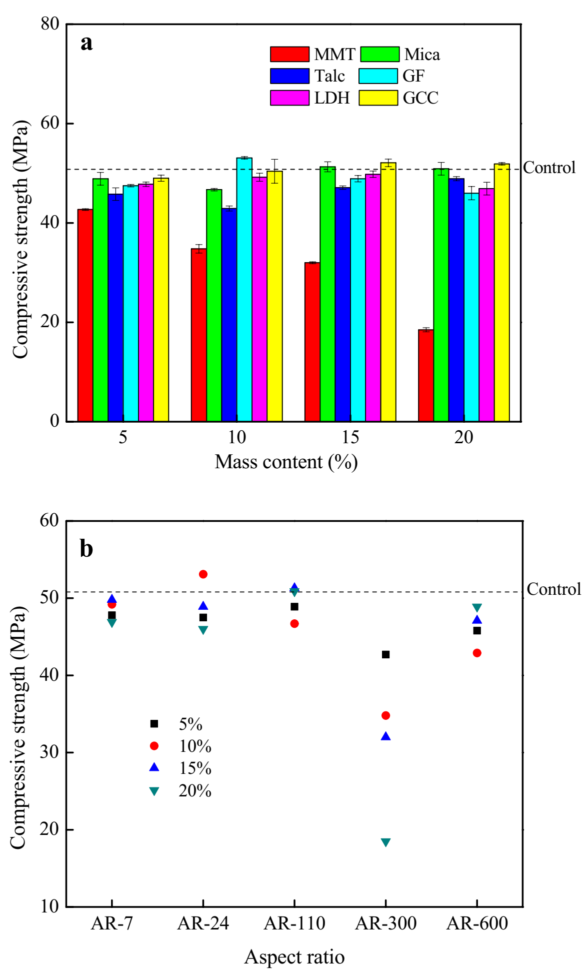

Fig. 2 Compressive strength of the modified EECM with different fillers. **a** Filler contents; **b** aspect ratios of fillers.

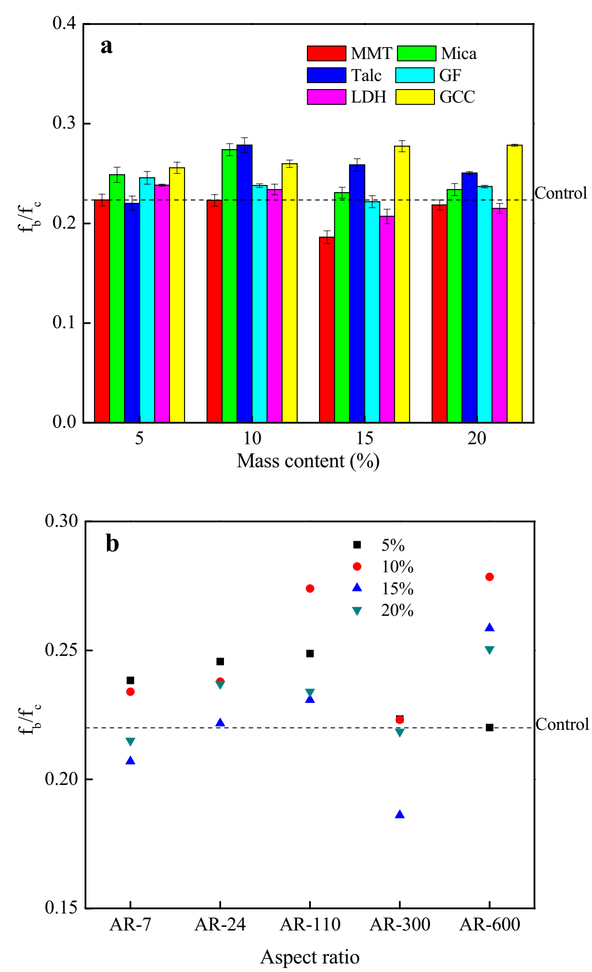

Fig. 3 F_b/F_c of the modified EECM with different fillers. **a** Filler contents; **b** aspect ratios of fillers.

water absorption badly affect the hydration of cement, and the strength of cement mortar gets worse, crack propagation can not be effectively prevented and the toughness of EECM modified by MMT becomes accordingly poor. It is worth pointing out that EECM modified by mica, talc and GF has higher f_b/f_c values. Once the modified EECM is damaged, extra energy is required to pull lamellar fillers out from cement, and thus consume the fracture energy and improve the toughness of modified EECM. As shown in Fig. 3b, all the f_b/f_c values of modified EECM were improved with the aspect ratio of lamellar filler increase, except that of the EECM with MMT.

By comparing the influences of six fillers on the mechanical properties of modified EECM, it is found that the improving effect of GCC on the flexural strength and f_b/f_c of EECM is superior to the other five lamellar fillers. It indicates that the filler size has little effect on the mechanical properties of modified EECM, and the surface characteristics of fillers play more important role. Moreover, EECM modified by MMT has the lowest mechanical properties maybe due to the strong water absorption of MMT. For these five kinds of lamellar fillers with similar surface characteristics, smaller aspect ratio and greater thickness are beneficial for the development of strength, while the larger aspect ratio is more conducive to the improvement of toughness.

3.2 Water Absorption

Porosity is a major feature of cement mortar, the macroporous structure of cement causes the greater water absorption. The ion of Cl^-, SO_4^{2-}, etc. can be transported by water and easily causes the correlative chemical reaction in cement and thus the decline of durability. Therefore, water absorption is usually an important parameter to measure the durability of cement. The water absorption of cement mortar is also affected by filler. On the one hand, filler can fill up the hole of cement in some degree and decease the water absorption; on the other hand, filler itself has some water absorption, especially some greater water absorption fillers are harmful to cement mortar. Therefore, the water absorption of modified EECM depends on which kind of effect takes an advantageous position.

Figure 4a shows the water absorption of modified EECM with different fillers after 28 days. As a whole, the water absorption of EECM is reduced after adding fillers except MMT, and the values have no obvious change along with the content of fillers. MMT has the similar effect of decreasing water absorption when its addition below 10%, however, once its content exceeding 10%, resulting in the water absorption of modified EECM remarkably increasing. Probably because the micro-aggregate filling effect of MMT is weaker than its own water absorption effect, and the hydration process of cement is impaired by MMT, the interfacial bonding between the EECM and MMT becomes weak, which results in the increasing water absorption of modified EECM (Chi and Huang 2012). By contrast, the water absorption of EECM becomes the lowest by adding GCC, due to its better micro-aggregate filling effect and lower water absorption compared to other fillers. The water absorption of lamellar filler is higher than GCC, and their micro-aggregate filling effects are lower than GCC. As can be seen in Fig. 4b, all the different aspect ratios of lamellar fillers reduced the water absorption of EECM, which is the combined result of micro-aggregate filling effect and blocking pore channel interaction. Moreover, the lamellar fillers with smaller aspect ratio devotes to the lower water absorption of EECM due to their better micro-aggregate filling effect.

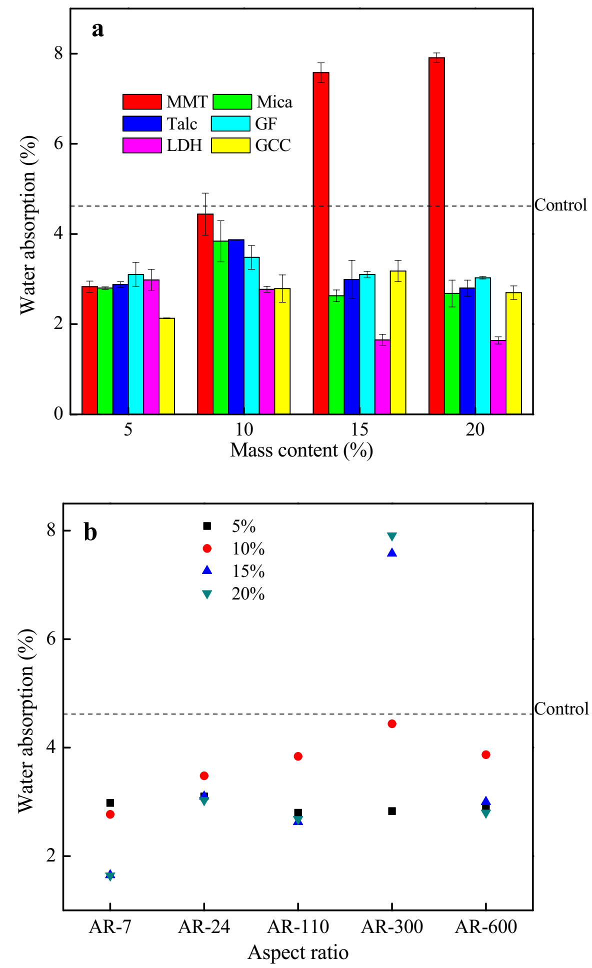

Fig. 4 Water absorption of modified EECM with different fillers. **a** Filler contents; **b** aspect ratios of fillers.

3.3 Rapid Chloride Migration

There are many pores with different sizes in cement mortar, and these pores become the transport channels of water and corrosive ions such as Cl^-, SO_4^{2-}, thus affecting the durability of cement mortar. Chloride penetration resistance is usually one of the important criterions for evaluating the durability of cement mortar.

As shown in Fig. 5a, the addition of MMT makes the chloride diffusion coefficient of EECM reduce significantly, and the highest decline amplitude reaches up to 58.3% compared with the control group. Kuo et al. (2006) also found that MMT played the similar role in cement mortar. It was attributed to that strong water absorption caused chloride ion adsorbed together and on the same time swelling effect of MMT also compactly fill the cement mortar. It is reported that the chloride permeability of Portland cement is not only related to its porosity and pore size, but also the adsorption and binding force of fillers affect the chloride diffusion (Yang et al. 2015; Andrade and Buják 2013). The chloride diffusion coefficient of EECM with GCC is higher than that of EECM with lamellar fillers, because the effect of GCC on impeding chloride penetration and migration is less than lamellar fillers. Figure 5b shows the chloride diffusion coefficient of EECM with different aspect ratios of lamellar fillers. On the whole, with the aspect ratio increases, the chloride diffusion coefficient of modified EECM decreased. Apparently, the larger aspect ratio of lamellar filler is favorable for hindering the transport of chloride; conversely, the blocking effect of fillers is weaker.

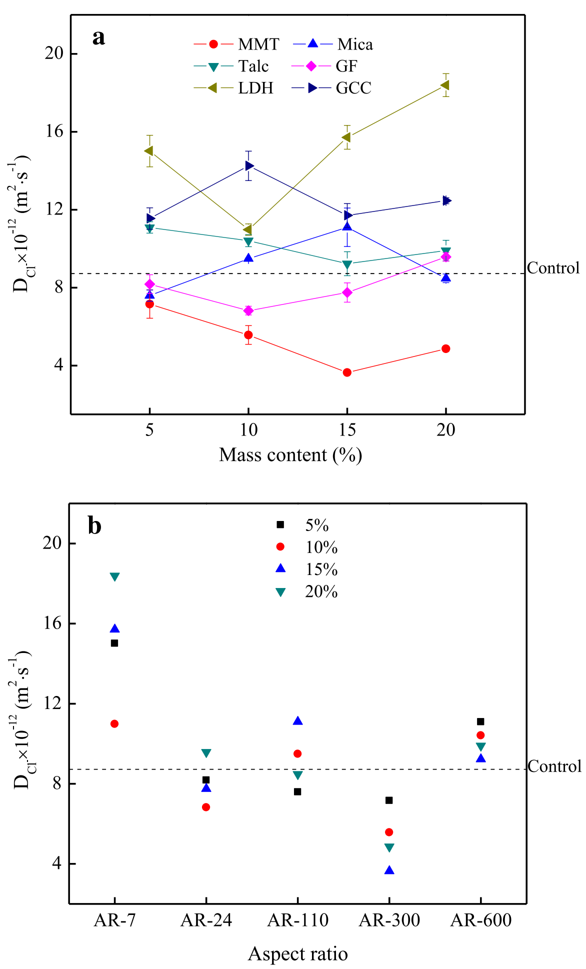

Fig. 5 Chloride diffusion coefficient of modified EECM with different fillers. **a** Filler contents; **b** aspect ratios of fillers.

3.4 Microstructure Analysis

Figure 6 shows the SEM micrograph of different fillers. GCC presents an irregular granular shape, which is more likely to induce stress concentration and crack deflection when EECM is damaged by stress, and beneficial to the toughness of EECM. Therefore, the filler with lamellar structure has no obvious advantage in increasing mechanical properties of EECM relative to the irregular granular filler. However, the lamellar structure of fillers has good barrier action on water and ions. The relatively larger aspect ratio of mica, talc and GF than the other lamellar fillers means larger contact area and stronger combination of fillers inserted in cement mortar. The desorption and pull-out process of lamellar fillers from cement mortar required to consume more energy when the mortar is loaded with stress, thereby resulting in the higher toughness of EECM. MMT and LDH have smaller diameter, the consumption energy during destruction is less than the other three kinds of lamellar fillers. Thus, the structural size of the lamellar filler has a great influence on the mechanical properties of EECM. Particularly, it is observed that MMT is consist of the stacked curly two-dimensional lamellar structure, which form a porous structure, it may be a reason for its high water absorption. Although this special structure of MMT causes the greater water absorption of EECM, the stacked coiled-sheet structure also can entrap the adsorbed chloride ion and enhance the resistance to chloride penetration of EECM.

Figure 7 represents the SEM micrograph of EECM with 10% content different fillers. The compactness of MMT modified EECM decreased (Fig. 7a), which is probably the reason that the stronger water absorption of MMT and result in the mechanical strength and the water resistance reduced, while the resistance to chloride penetration is improved perhaps owing to the greater adsorbability of MMT. The EECM structure with mica (Fig. 7b) and talc (Fig. 7c) are looser than the EECM structure with LDH, they have higher water absorption. Figure 7d shows the SEM micrograph of GF modified EECM with

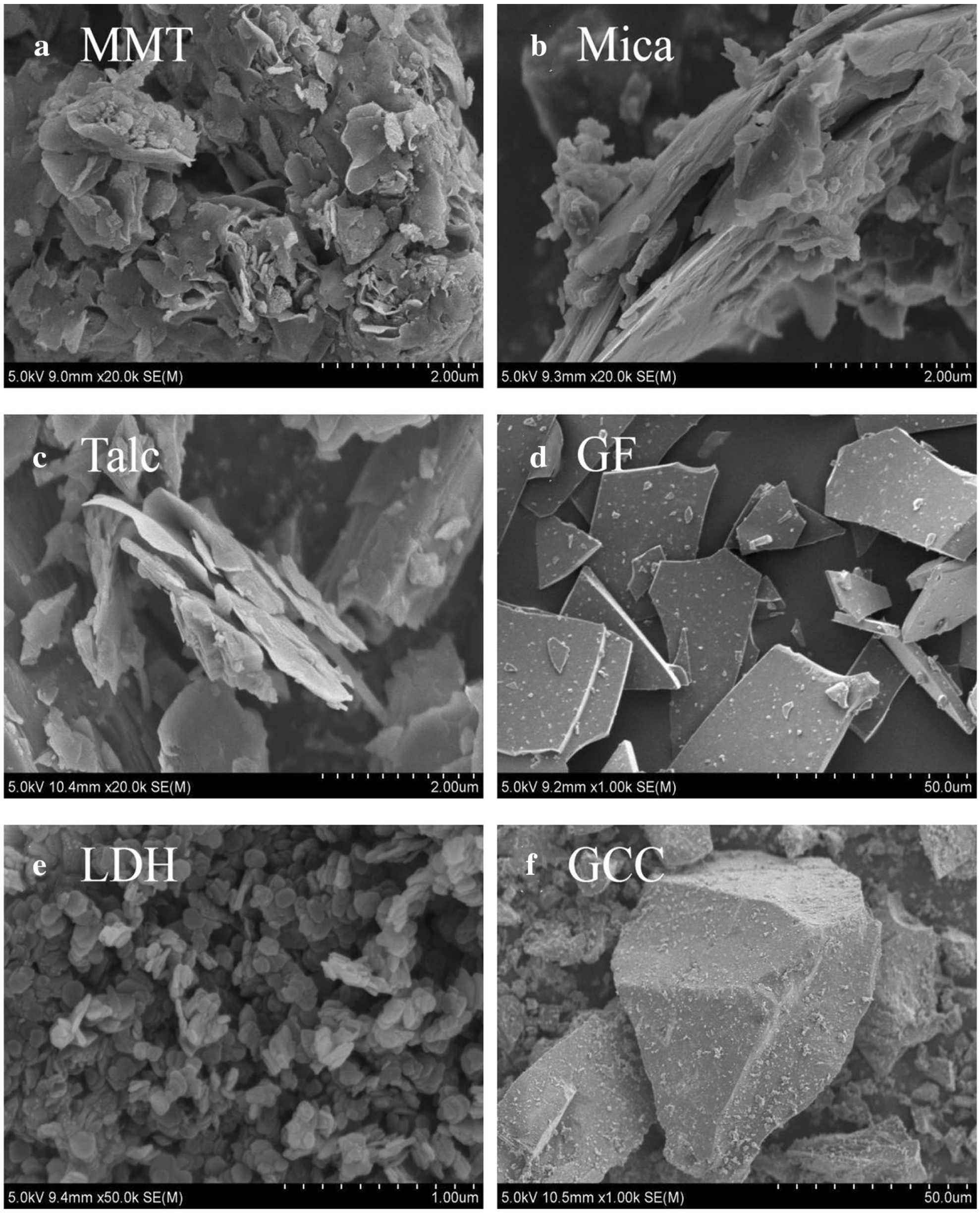

Fig. 6 The SEM micrographs of fillers **a** MMT; **b** mica; **c** talc; **d** GF; **e** LDH; **f** GCC.

good micro-aggregate filling effect, the lamellar structure obstructs some channels and enhances the chloride penetration resistance of EECM. As shown in Fig. 7e, LDH with small aspect ratio displays a good filling effect in the EECM, which is beneficial to improve the compressive strength and reduce the water absorption of EECM. Although GCC has the obvious micro-aggregate filling effect, the structure of mortar is still loose and not optimized significantly (Fig. 7f), and thus the resistance to chloride penetration of composites remains unchanged.

4 Conclusion

In this paper, the effects of six kinds of fillers on the mechanical strength, water absorption and chloride diffusion coefficient of modified EECM were studied. It is found that the performances of modified EECM were closely related to the microstructure of fillers.

The flexural strength and f_b/f_c of EECM were both improved significantly by incorporating GCC. However, it revealed that lamellar fillers had no advantages in mechanical strength compared with granular filler, while

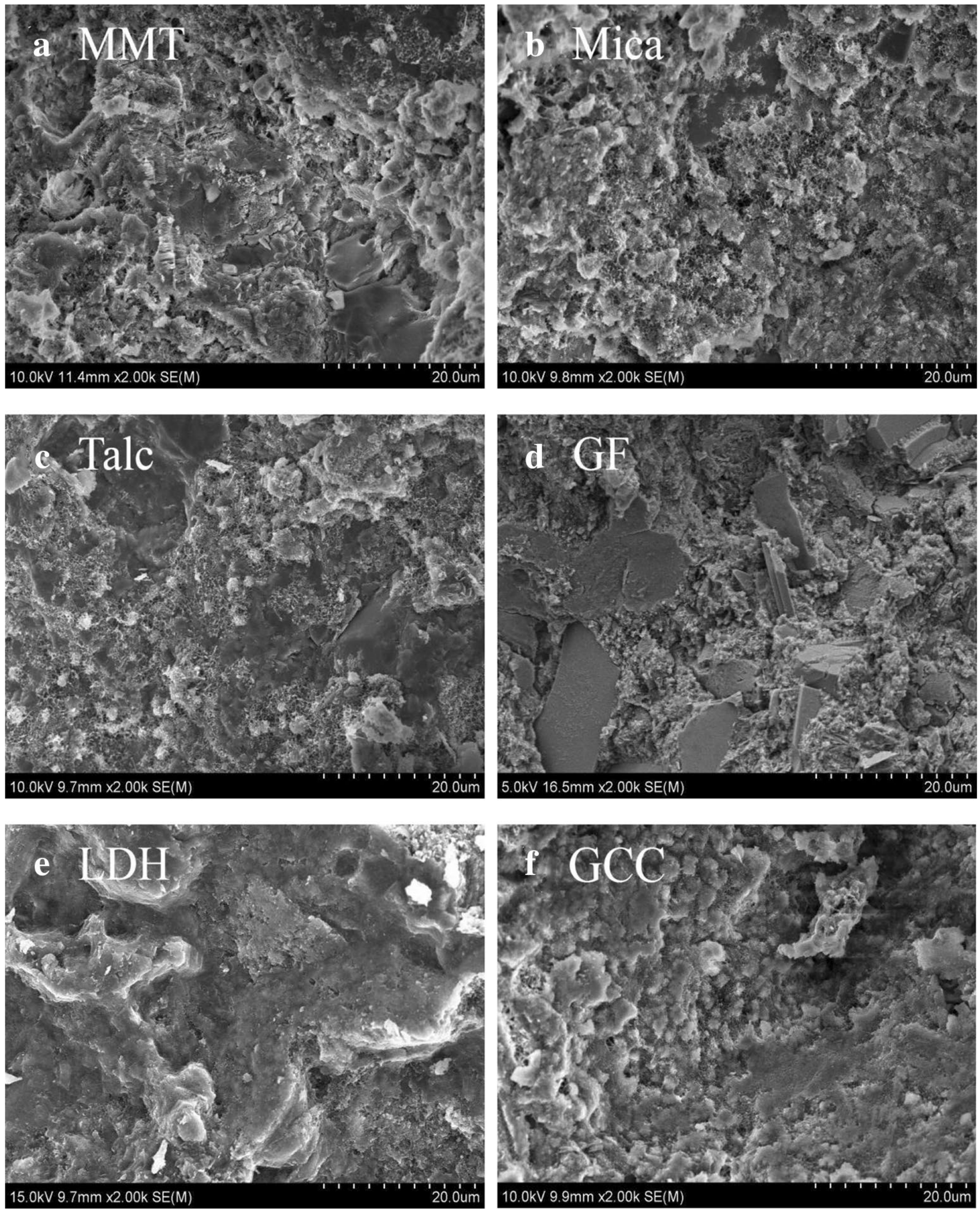

Fig. 7 The SEM micrograph of modified EECM with different fillers. **a** MMT; **b** mica; **c** talc; **d** GF; **e** LDH; **f** GCC.

the surface characteristics of fillers had obvious effect on the mechanical properties. The mechanical strength of modified EECM increased first and then decreased with the increase of aspect ratio, and the greater thickness was also beneficial to enhanced the compressive strength. While the larger aspect ratio was more conducive to the improvement of toughness, except MMT.

The addition of all fillers caused the decline of water absorption of EECM, but MMT above 10 wt% made water absorption of modified EECM higher than that of control group, probably due to its own greater surface water absorption. It showed that water absorption of modified EECM together decided by the micro-aggregate filling effect and surface water absorption of fillers. Among the lamellar fillers, the smaller aspect ratio could obtain the lower water absorption of EECM.

The lamellar fillers were superior to GCC in resisting chloride penetration, and the chloride diffusion coefficient of modified EECM decreased first and then increased with the increase of aspect ratio. Especially the chloride diffusion coefficient of EECM with 15% MMT reduced by 58.3%, compared with the control group.

For the selected five kinds of the lamellar fillers, the smaller aspect ratio caused better micro-aggregate filling effect, which is beneficial to the improvement of the strength and water resistance of modified EECM. The larger aspect ratio of the filler was more beneficial to enhance the toughness and resistance to chloride permeability of modified EECM.

5 Highlights

1. The lamellar fillers can improve the chloride ion permeability resistance and reduce water absorption of EECM.
2. The lamellar fillers with lower aspect ratio (AR) can provide the better strength and water resistance for EECM.
3. The lamellar fillers with higher AR can improve the chloride ion permeability resistance of EECM.

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Authors' contributions
JZ and BD have designed the experimental program and helped in the analysis. HL has carried out the experimental work, run the analysis and prepared the first draft of the paper. BD and FX have helped in the analysis and finalizing the paper. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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