EFFECT OF PASTE CONTENT ON LONG-TERM STRENGTH AND DURABILITY PERFORMANCE OF GREEN MORTARS

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Abstract

This study uses densified mixture design algorithm (DMDA) to design the mixture proportions green mortars incorporating fly ash and ground granulated blast furnace slag (GGBFS). Three green mortar mixtures with various paste contents were designed using the DMDA method while a control cement-based mortar mixture was designed using the conventional method for comparison. The effect of different paste contents (n = 1.1, 1.3, and 1.5) on the changes of porosity, thermal conductivity, compressive strength, chloride ion penetration, resistance to sulfate attack, and ultrasonic pulse velocity (UPV) of both the green and control mortars was studied. The procedures of DMDA mix design for green mortar mixtures were also presented in this study. Test results reveal that all three green mixtures show a better performance than the control mixture, especially for long-term properties. On the other hand, increasing paste content increased porosity and compressive strength, however, it reduced thermal conductivity and UPV of the green mortars. All of the green mortars exhibited good performance with low porosity and compressive strength values of above 40 MPa after 28 days of curing. Moreover, the green mortars also demonstrated excellent ability to resist chloride (with RCPT values significantly lower than the threshold of 1000 coulombs) and sulfate attacks. As a result, the quality of these mortars was classified as very good level with UPV values of above 4000 m/s. This study proves the effectiveness of using the DMDA method to design the green mortar mixtures in the combination of using fly ash and GGBFS.

Keywords: green mortar; paste content; DMDA method; fly ash; GGBFS; durability.

1. Introduction

As well as industrialization and modernization, the process of urbanization is rapidly exploring in Vietnam. Consequently, the demand for construction materials for infrastructure development also increases quickly. In the context of natural resources being gradually depleted, the efficient and economical use of construction materials is an urgent issue. To save materials, high strength and sustainable materials are being interested in and developed by domestic and foreign researchers. Besides, the partial or full replacement of traditional materials in construction materials such as cement and natural river sand by alternative materials is also being interesting. Previous studies have indicated that

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the process of cement production releases a huge quantity of carbon dioxide, negatively influencing the environment [1–3]. In addition, several industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), which are respective by-products from coal-based thermal power plants and steel factories, are annually discarded into the environment with a large quantity and the quantity of these by-products is increasing daily. For instance, in Vietnam, about 16.4 million tons of ashes were released in 2019 [4] and about 1.12 million tons of GGBFS are also generated in 2021. As estimated, the amount of both fly ash and GGBFS will increase in the next few years. Thus, to reduce this amount of industrial by-products, the Vietnamese Government has promulgated several policies to encourage the recycling of these by-products in construction activities, especially in the production of construction materials.

So far, natural river sand has been conventionally used as fine aggregate in mortar and concrete production in Vietnam. However, it is a limited natural resource and is currently being exploited over the allowance, leading to erosion and seriously impacting the aquatic life and people who lived on the side of the river [5, 6]. According to the Vietnamese Ministry of Construction, the current reverse of river sand is only around 2 million cubic meters. With the current rate of sand consumption, likely, there will not be enough river sand for construction activity in the coming years. To face this issue, the use of artificial sand such as industrial solid wastes and crushed sand to replace river sand is considered. In addition, important projects such as high-rise buildings and coastal structures require materials with high strength and high resistance to chemical attacks. Therefore, the use of crushed sand as fine aggregate in the production of mortar needs to be examined, especially for durability properties. Following this trend, the use of fly ash, GGBFS, and crushed sand in producing the green mortar is investigated in this study. Similar to green concrete [7] or green building materials [8], the term "green mortar" is also defined as a mortar that uses waste material/ by-product as one of its components. In addition, the production process of green mortar does not lead to environmental destruction. It also has high performance and life cycle sustainability.

To enhance the quality of mortar, several researchers have proposed different methods to design mortar mixtures [9–12]. Besides, the densified mixture design algorithm (DMDA) has been recognized as an effective method to improve the strength and durability of concrete [13], which may apply for mix design of the green mortars with consideration on both long-term strength and durability performance. The main objective of this method is to minimize the void volume between aggregates. In which, the paste content is assumed as void volume times coefficient n ($n = 1.1 - 1.5$). Based on this method, the water and cement content is also reduced and the highest density of the concrete is achieved, thus increasing the concrete properties. Although, this method has been applied to reduce the negative effect of recycled aggregate in the production of concrete [14, 15], the use of this method in mortars is still limited. Moreover, in previous studies, paste coefficient (n) was fixed [13–15], so the influence of paste content on the properties of resulting products has not been investigated, especially the long-term strength and the resistance to chemical attack.

To address the abovementioned research gaps, in this study, the DMDA method was used to design green mortar mixtures using crushed sand as fine aggregate and incorporating fly ash and GGBFS as a portion of binder material. Especially, the modified DMDA method for mortar mixture design will be detailedly presented in this study. To clarify the effectiveness of the DMDA mix design method, the properties of these green mortars are compared with that of the control cement-based mixture, which was designed using the conventional method. The use of crushed sand instead of river sand helps to limit the shortage of river sand and make the efficient in using natural resources. This study is also contributed to recycling a part of local fly ash into construction materials, serving for sustain-

able development. Moreover, green mortars with relatively high strength and excellent durability were introduced as efficient, economical, and sustainable materials for the construction industry. Furthermore, the influence of paste content on the long-term performance of the green mortars was investigated through the measurements of porosity, thermal conductivity, compressive strength, resistance to sulfate attack, chloride ion penetration (RCPT), and ultrasonic pulse velocity (UPV).

2. Materials and experimental methods

2.1. Materials

In this study, the ingredients of green mortar included cement (type PCB40 of Insee company), fly ash (type F from Duyen Hai thermal power plant), GGBFS (type S95 from Hoa Phat corporation), crushed sand, water, and superplasticizer (SP). The densities of cement, fly ash and GGBFS were 2.84, 2.14, and 2.85 T/m^3, respectively. The chemical compositions of these materials are shown in Table 1. The crushed sand with density of 2.84 T/m^3, fineness modulus of 3.55, water absorption of 1.42%, and the maximum particle size of 5 mm was used as fine aggregate in mortar mixtures. The SP of type G with a density of 1.15 T/m^3 was used to control the workability of fresh mortar mixtures with a flow diameter of 180 ± 5 mm. Tap water was used for mixing.

Table 1. Chemical compositions of cementitious materials

Materials	SiO_2 (wt.%)	Al_2O_3 (wt.%)	Fe_2O_3 (wt.%)	MgO (wt.%)	CaO (wt.%)	SO_3 (wt.%)	Others (wt.%)	LOI (wt.%)
Cement	21.8	3.1	4.8	62.1	3.6	2.8	1.0	0.8
FA	58.8	5.6	26.1	2.1	1.7	0.2	1.8	3.7
GGBFS	38.0	0.6	13.1	36.8	5.8	1.4	0.9	3.4

2.2. Mixture proportions

As previously mentioned, the ingredient proportions of green mortars were designed using the DMDA procedure. Meanwhile, the control mortar mixture using only cement as binder material was designed using the conventional method. In DMDA, the mortar mixtures are comprised of the paste and aggregate phases with the respective functions of lubricating and filling pores to achieve workability and strength, creating the superstructure of the system. In which, paste phase included cement, a part of fly ash, GGBFS, water, and SP while the aggregate phase included crushed sand and the remainder of the fly ash. In this study, fly ash was used to fill the voids between the crushed sand particles to minimize the void volume of the system in order to reduce the cement paste in the mixture and enhance the performance of the mortars. Besides, fly ash also plays as a pozzolanic material in the system. The standard operating procedures for the DMDA mix design of concrete were previously reported by Hwang's research group [13, 16]. Thus, a modified DMDA mix design was applied for mix design of mortar mixtures was presented in the present study, including the following main steps:

Step 1. Proper selection of raw materials

In this step, the physical properties of each ingredient used for the preparation of mortars are checked to ensure quality control.

Step 2. Packing optimization of the dry density of aggregate phase

With the particle sizes are significantly smaller than those of crushed sand, fly ash is used to fill the voids between the crushed sand particles (through α test). After the α test, the quantities of both fly ash and crushed sand corresponding to the highest density of blended materials are determined, with the maximum weight ratio of blended fly ash and crushed sand ($\alpha_{\max}$, %) as presented in Eq. (1):

$$\alpha_{\max} = \frac{W_{fa}}{W_{fa} + W_{cs}} \tag{1}$$

where W_{fa} and W_{cs} are the weights of fly ash and crushed sand (kg), respectively.

Step 3. Proportion of mortar ingredients

Determine the void volume: The volume of the void space (V_{void}, m³) among the aggregates is calculated using Eq. (2):

$$V_{void} = 1 - \left(\frac{W_{fa}}{\gamma_{fa}} + \frac{W_{cs}}{\gamma_{cs}} \right) \tag{2}$$

where γ_{fa} and γ_{cs} are the densities of fly ash and crushed sand $\left(\text{kg/m}^3 \right)$, respectively.

Determine the required lubricating paste volume: The minimum volume of cement paste required (V_{paste}, m³) is estimated through Eq. (3).

$$V_{\text{paste}} = V_{void} + (S \times t) = n\, V_{void} \tag{3}$$

where S = the surface area of aggregates (m²); t = the thickness of the lubricating paste on aggregate surfaces (μm); n = a multiplier for lubricating paste.

It is noted that multiplying V_{void} with a coefficient (n) is necessary to account for the lubricating layer ($S \times t$) on the aggregate surface (S) to ensure concrete workability in practice. Moreover, various n coefficients have been suggested to obtain a desired level of workability due to the difficulty in determining ($S \times t$) layer.

Calculate quantities of fly ash and crushed sand: The total volume of aggregate (V_a, m³) is determined using Eq. (4):

$$V_a = 1 - V_{paste} \tag{4}$$

Then, the quantities of fly ash and crushed sand can be calculated using Eqs. (5) and (6), respectively.

$$W_{fa} = W_{cs} \times \left(\frac{\alpha}{1 - \alpha} \right) \tag{5}$$

$$W_{cs} = \frac{V_a}{\left(\dfrac{\alpha}{1 - \alpha} \right) \dfrac{1}{\gamma_{fa}} + \dfrac{1}{\gamma_{cs}}} \tag{6}$$

Calculate the amount of cement, mixing water, and GGBFS: In the case of using GGBFS as a partial substitute for cement, the volume of lubricating paste (V_{paste}, m³) is obtained using Eq. (7):

$$V_{paste} = \frac{W_w}{\gamma_w} + \frac{W_c}{\gamma_c} + \frac{W_{slag}}{\gamma_{slag}} \tag{7}$$

where W_w, W_c, and W_{slag} are the weights of water, cement, and GGBFS while γ_w, γ_c, and γ_{slag} are the densities of water, cement, and GGBFS, respectively.

The ratio of the GGBFS used to partially replace cement is expressed as ξ, and is calculated using Eq. (8):

$$\xi = \frac{W_{slag}}{W_{slag} + W_c} \tag{8}$$

Thus, Eq. (7) can be rewritten as Eq. (9):

$$V_{paste} = \frac{\left(\dfrac{W_w}{W_c}\right) W_c}{\gamma_w} + \frac{W_c}{\gamma_c} + \frac{\left(\dfrac{\xi}{1-\xi}\right) W_c}{\gamma_{slag}} \tag{9}$$

The water/binder (w/b) ratio is expressed as λ, and calculated using Eq. (10), then the quantities of mixing water and GGBFS are calculated using Eqs. (11) and (12), respectively:

$$\lambda = \frac{W_w}{W_c + W_{fa} + W_{slag}} \tag{10}$$

$$W_w = \lambda \left(W_c + W_{fa} + W_{slag} \right) \tag{11}$$

$$W_{slag} = \left(\frac{\xi}{1-\xi} \right) \times W_c \tag{12}$$

Substituting Eqs. (11) and (12) into Eq. (9) to determine the quantity of cement as expressed in Eq. (13):

$$W_c = \frac{V_{paste} - \lambda \left(\dfrac{W_{fa}}{\gamma_w} \right)}{\left[\dfrac{\lambda}{\gamma_w} + \dfrac{1}{\gamma_c} + \left(\dfrac{\xi}{1-\xi} \right)\left(\dfrac{\lambda}{\gamma_w} + \dfrac{1}{\gamma_{slag}} \right) \right]} \tag{13}$$

Determine the dosage of SP and water adjustment: The SP dosage is determined depending on the water content. Normally, the SP dosage is estimated based on prior experience and the workability of a trial batch of the mortar mixture. In addition, the amount of water is also adjusted according to the water absorption of crushed sand.

The above procedures were applied for calculating the material proportions of the green mortars with the results as shown in Table 2. With the scope of the study, three green mortar mixtures with different paste contents (n = 1.1, 1.3, and 1.5, denoted as N1.1, N1.3, and N1.5 mixtures) were prepared

Table 2. Mixture proportions of mortar samples

Sample code	Material proportions (kg/m^3)					
	Cement	Fly ash	GGBFS	Crushed sand	Water	SP
PCB	569.1	0	0	1621.7	227.6	1.22
N1.1	227.1	97.3	163.8	1741.6	195.2	1.10
N1.3	284.5	121.9	150.6	1600.2	222.8	0.55
N1.5	342.1	146.6	137.2	1458.6	250.4	0.00

using a fixed w/b ratio of 0.4. Besides, a small amount of SP was used to adjust the flow diameter of the fresh mortar mixtures in the range of 180 ± 5 mm. It is noticed that the control mortar mixture (denoted as PCB as shown in Table 2) was also designed with the same w/b ratio and its flow diameter was similar to that of the green mortar mixtures.

2.3. Sample preparation

The mortar ingredients were prepared based on their proportions noted in Table 2. Water and SP were mixed before being used. Cement, fly ash, and GGBFS were then dry mixed for about 2 minutes using a laboratory mixer. While mixing, a part of water-SP was added into the mixer, and mixing continued for another 2 minutes to obtain a homogeneous paste. Next, crushed sand was added to the paste followed by the remaining part of water-SP and mixed for additional 2 minutes. Finally, the finished mixture was used to prepare the mortar samples for various tests as described in the next section. In this study, the mortar samples were removed out of the molds 24 hours after casting and stored in different conditions as required for each test method.

2.4. Test methods

(a) Test of compressive strength

(b) Determine length change due to sulfate attack

(c) Determine suspension weight for porosity calculation

(d) Determine rapid chloride ion penetration

(e) Determine ultrasonic pulse velocity

(f) Determine thermal conductivity

Figure 1. Apparatus used for the experiments

Fig. 1 introduces the apparatus used for the evaluation of mortar's properties including compressive strength (Fig. 1(a)), resistance to sulfate attack (Fig. 1(b)), porosity (Fig. 1(c)), RCPT (Fig. 1(d)),

UPV (Fig. 1(e)), and thermal conductivity (Fig. 1(f)). In detail, the compressive strength of the mortars was measured on the half of $40 \times 40 \times 160$ mm prismatic samples at 1, 7, 28, and 56 days following the TCVN 3121-11:2003 [17]. It is noted that the samples used for the compressive strength test were obtained from the broken prisms in flexure as stated in TCVN 3121-11:2003 [17]. In addition, the cubic mortar samples of $50 \times 50 \times 50$ mm were used for the tests of porosity and thermal conductivity. These tests were conducted at 28 and 56 days following the procedures described by Huynh et al. [18, 19]. It is noted that the thermal conductivity test was performed on the mortar samples at oven-dry condition. The prismatic samples with a dimension of $25 \times 25 \times 285$ mm were used to measure the change in length of the sample immersed in sulfate solution based on TCVN 7713:2007 [20]. Besides, the cylinder samples with dimensions of 100 mm diameter and 200 mm height were used for UPV measurement in compliance with TCVN 9357:2012 [21], while the cylinder samples with the diameter of 100 mm and the height of 50 mm were used for the RCPT test as per TCVN 9337:2012 [22].

3. Results and discussion

3.1. Porosity

The purpose of using the DMDA method is to reduce the porosity of mortars in order to enhance the mortars' properties. The porosity of all mortars was measured and plotted in Fig. 2. According to Fig. 2, the porosity of the green mortars increased with increasing paste content and these values were found to reduce with curing time. The porosity values of DMDA mortars ranged from 8.8% to 11.1% at 28 days and from 7.9% to 10.4% at 56 days. It is noted that aggregates are likely to be denser and have lower permeability than cement paste. Therefore, mortars with higher paste content tend to have higher porosity, leading to volumetric stability problems [23, 24]. On the other hand, the reduction of porosity with time is due to the increased amount of hydration products during the curing time, filling voids, and compacting the mortar's structure [25, 26].
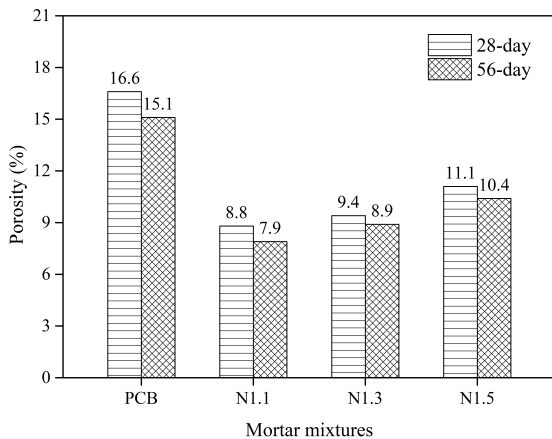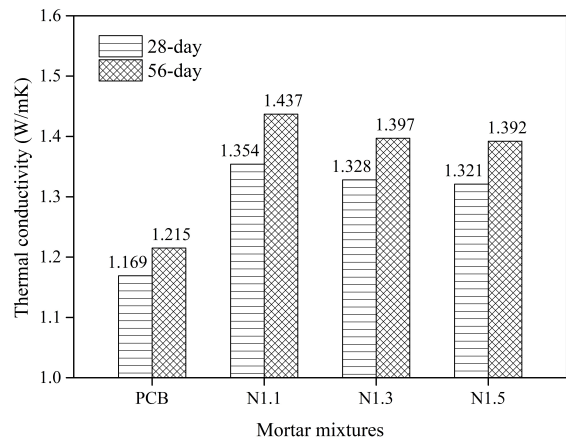

Figure 2. Porosity of mortar samples

Figure 3. Thermal conductivity of mortar samples

The porosity results showed that the N1.1 samples had the lowest porosity among the three green mortars. This means that the paste coefficient $n = 1.1$ is the most effective to reduce the void volume of mortar in comparison with the other two paste coefficients. This study also found that all of the green mortars exhibited significantly lower porosity levels than the control mortar (PCB samples) and

also lower than those values reported in previous studies [27, 28]. The influence of porosity on other properties of the mortars will be discussed in the next sections.

3.2. Thermal conductivity

The results of thermal conductivity measurement for all mortar samples at 28 and 56 days are shown in Fig. 3. For green mortars, thermal conductivity values measured at 28 and 56 days were in the respective ranges of 1.321 – 1.354 W/m.K and 1.392 – 1.437 W/m.K. The thermal conductivity of the green mortars was found to be decreased with increasing the paste coefficient and the thermal conductivity values at 56 days were higher than the corresponding value at 28 days. The thermal conductivity strongly depends on the density of the samples [29–31], thus it is also closely associated with the porosity of the samples. Indeed, the higher the porosity, the lower the thermal conductivity is. As mentioned above, more hydration products were formed with curing time, thus the internal structure of mortar samples at 56 days was believed to be denser than that of the samples at 28 days. Fig. 3 also reveals that the thermal conductivity of the DMDA mortars was significantly higher than that of the control mortar. This result is in line with the porosity result as shown in Fig. 2. Also, the green mortars developed in this study registered thermal conductivity values relatively higher than the values reported in previous studies [31, 32]. This is attributable to the low porosity of the green mortars designed by the DMDA method.

3.3. Compressive strength

The strength capacity of mortar is expressed through the value of compressive strength as shown in Fig. 4. As observed in Fig. 4, the 1-day compressive strength of the green mortars was slightly lower than that of the control mortar. This is due to the lower pozzolanic reaction of fly ash and GGBFS incorporated in DMDA mortars as compared to the cement hydration in the control mortar [33]. However, after 7 days, the green mortars earned higher compressive strength than the control mortar, more significant at 28 and 56 days. This finding may be attributable to the effectiveness of both packing density and chemical reactions of the DMDA method, reducing void volume and improving the long-term strength of the green

Figure 4. Compressive strength of mortar samples

mortars [13]. Once again, this result proves the superior long-term strength of the DMDA mortar in comparison with the conventional (control) mortar.

As shown in Fig. 4, the compressive strength of the green mortars increased with curing time and paste content. Indeed, the green mortar with a paste coefficient of $n = 1.5$ (N1.5) had the highest compressive strength, followed by the N1.3 and N1.1 mortars. In general, the compressive strength of mortar is often associated with its porosity [27]. The lower porosity results in the higher compressive strength. Besides, it is noticed that the compressive strength of mortar depends on the strength capacity of paste and aggregate, and the strength capacity of aggregate is generally higher than that of paste. However, the compressive strength of the green mortars prepared in this study did not follow the general trend as above mentioned. In this case, the lower compressive strength of the green mortar
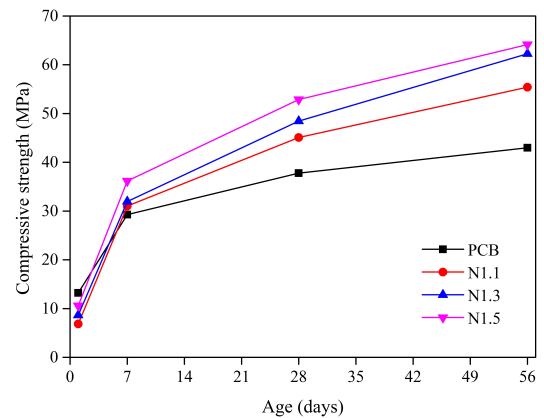
prepared with a paste coefficient of $n = 1.1$ is likely due to the lower strength capacity of aggregate in comparison with that of the paste. Among the green mortar mixtures, the N1.1 mixture comprised the highest amount of aggregate (see Table 2). During the experiment, it was found that the aggregate phase of this sample was firstly broken under a compression load, leading to the reduction in compressive strength. Meanwhile, the N1.3 and N1.5 mixtures with a high amount of paste showed a higher compressive strength due to the superior strength of the paste phase than that of the aggregate phase. More experiments are required to clarify this behavior. As a result, all green mortar samples in this study gained the compressive strength values at 28 and 56 days of above 45 and 55 MPa, respectively. These values are significantly higher than the compressive strength of popular mortars used in practice (20 – 40 MPa). It also noticed that although the green mortar mixture designed using a paste coefficient of $n = 1.1$ had a lower compressive strength than the other two mixtures, its 28-day compressive strength was still higher than 40 MPa, indicating good quality. In addition, the use of less paste content contributes to saving the cement content and reducing the construction costs. In real practice, the paste coefficient is selected depending on the specific requirement, so that the mortar has a suitable compressive strength for the target applications.

3.4. Rapid chloride ion penetration

The ability of mortar to resist the chemical attack by chloride ions is expressed in terms of the total charge passed through the mortar sample as shown in Fig. 5. It can be seen that the control mortar (PCB sample) had a significantly higher RCPT value than the green mortars. A previous study [34] has proved that the RCPT values increased with increasing the porosity. In this study, the void volume of the green mortars was minimized due to the effectiveness of the DMDA method, leading to a significantly lower RCPT value in comparison with the control mortar. For instance, the total charge passed through the green mortar samples at 28 and 56 days was in the ranges of 294 – 511

Figure 5. RCPT of mortar samples

coulombs and 219 – 458 coulombs, respectively. In other words, the resistance of the green mortars to the chloride ion penetration was reduced with increasing paste content and the chloride ion penetration resistance of the green mortars increased along with curing time. As shown, the N1.5 sample had the highest porosity (see Fig. 2) and thus the highest RCPT value (see Fig. 5) as compared to the N1.1 and N1.3 samples. Meanwhile, the N1.1 mixture exhibited the highest resistance to the chloride ion penetration because it registered the lowest porosity among the three green mortar mixtures (Fig. 2). As the above discussion, the porosity of the mortars is reduced due to the generation of more hydration products along with curing time, resulting in the low RCPT value as shown in Fig. 5. According to TCVN 9337:2012 [22], all of the mortars prepared in this study are classified in excellent resistance to chloride attack catalog with RCPT values significantly lower than the threshold of 1000 coulombs. The high resistance of these green mortars to chloride ion penetration is attributable to physically packing and chemically reacting of mortar's ingredients under the DMDA mix design. In addition, the incorporation of fly ash and GGBFS also contributes to enhance the resistance to chemical attack of the green mortars due to the reduction of internal pores filled by the hydration products [35, 36].
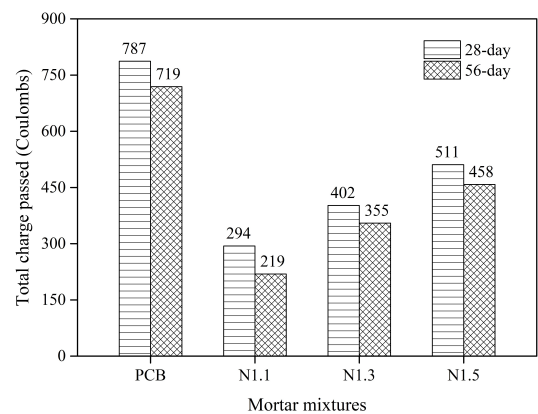
It means that the combination of supplementary cementitious materials in DMDA can improve the resistance to chloride ion penetration.

3.5. Resistance to sulfate attack

The resistance to sulfate attack is presented through the change in length of the mortar samples immersed in a sulfate solution, with the results as shown in Fig. 6. Under the penetration of sulfate ion, a series of complex chemical reactions occurred inside the mortar samples and formed the ettringite and gypsum, causing the expansion and inducing the micro cracks, greatly affecting the durability properties of mortars. Fig. 6 shows that the expansion rate was relatively high before 28 days, then slowly later on. In detail, the control mixture showed the highest change in length, orderly followed by the green mortar with $n = 1.5$, 1.3, and 1.1. It means that the expansion of the mortar designed using the conventional method is

Figure 6. Change in length of mortar samples immersed in a sulfate solution

higher than that of the green mortars designed using the DMDA method, and the green mortars with higher paste content tended to expand more. As aforementioned, the resistance of mortar to chemical attack is closely related to its porosity. Therefore, the mortars with higher porosity are easy to be penetrated by chemical ions. However, the change in length of all green mortar samples in this study was still significantly lower than that of the control mixture and also lower than the values reported by Santhanam et al. [37]. The lower expansion rate in green mortars is contributable to both the filler and pozzolanic effects of DMDA as already mentioned in section 2.2. Moreover, the use of fly ash and GGBFS also help to improve the resistance to sulfate attack [38–40]. These findings prove that all green mortars in this study exhibited an excellent ability to resist chemical attacks for both chloride and sulfate ions.

3.6. Ultrasonic pulse velocity

The UPV test is one of the commonly used non-destructive tests to evaluate the relative quality of concrete and mortar samples [41, 42]. The UPV value represents the homogeneity as well as the existence of cracks and voids inside the samples. The UPV values of all mortars in this study were measured at 28 and 56 days and plotted in Fig. 7. The UPV value of the control mortar (PCB sample) was lower than those of the green mortar samples. In line with the previous discussion (Sections 3.1 and 3.3), the less void volume (lower porosity) and the enhanced long-term strength of the green mortars in comparison with the control mortar may be attributable to the effectiveness of

Figure 7. UPV of mortar samples

both packing density and chemical reactions of the DMDA [13]. As a result, the less-dense structure

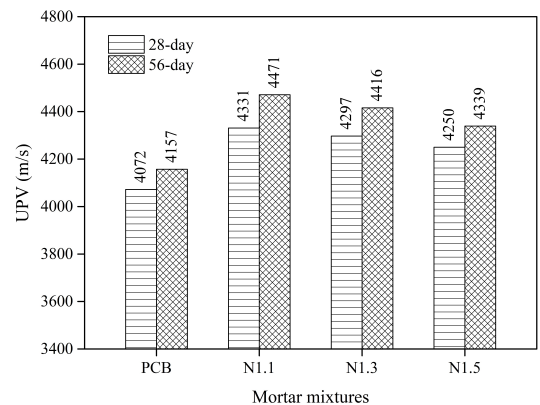of the control mortar makes its UPV lower than that of the green mortars. In addition, the UPV values of the green mortars reduced as increasing the paste content and increased with curing time. This is in line with the development in compressive strength of the mortars. In detail, the green mortar samples prepared with the paste coefficients of n = 1.1, 1.3, and 1.5 had the UPV values of 4331, 4297, and 4250 m/s at 28 days and corresponding values at 56 days were 4471, 4416, and 4339 m/s. A previous study [43] has indicated that the UPV value of mortar is greatly affected by its density as well as its porosity. The sample with high porosity has a low UPV value. The UPV results obtained in Fig. 7 are in good agreement with the porosity and compressive strength results as presented in Figs. 2 and 4, respectively. For instance, the control mortar with the highest porosity exhibited the lowest UPV value. For the green mortars, increasing paste content was found to raise the porosity, which consequently reduce their UPV values. In addition, all green mortars prepared in this study obtained UPV values of above 4000 m/s, which are classified as a very good to excellent quality [41, 42]. Again, this finding demonstrates the effectiveness of using the DMDA method combined with fly ash and GGBFS to design green mortar mixtures.

4. Conclusions

In this study, the DMDA method is used to design the green mortar mixtures containing crushed sand as fine aggregate and fly ash and GGBFS as binder materials. The effectiveness of using the DMDA method and the influence of paste content on the engineering properties of the green mortars were investigated. In addition, comparative performance of the mortar design by conventional method and green mortars designed by DMDA method is also included in this study. Based on the experimental results, the following major conclusions can be drawn:

- Paste content was found to significantly affect the engineering properties and durability performance of the green mortars. Increasing paste content led to an increase in porosity and RCPT while the thermal conductivity, UPV, and sulfate resistance of the green mortars were reduced. Besides, this study found that compressive strength increased with increasing paste content in the mortar mixtures. Thus, further experiments are required to clarify this behavior.

- As compared to the control mortar, all of the green mortars exhibited superior performance, especially in long-term ages, in terms of porosity, thermal conductivity, compressive strength, RCPT, sulfate resistance, and UPV. This finding confirms the effectiveness of using the DMDA for the mix design of the green mortars mixtures.

- All of the green mortars prepared in this study revealed good quality with relatively low porosity, high compressive strength, high UPV, and excellent resistance to chloride and sulfate attacks. Based on the obtained results, the N1.1 was suggested as the optimal mixture, which achieved high mechanical strength and better long-term durability. In addition, the use of less paste content in the N1.1 mixture may not only limit the use of cement for a cleaner environment but also provide cost-effectively.

- The results of this study support the application of the DMDA method for mixture design of the green mortars with consideration of both long-term strength and durability. In light of the limitation of this study, the effect of paste content on the compressive strength development of the green mortars is an issue that needs further investigation and clarification.

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