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Original research article

# pH-assisted strength gain projection for green cement mortar composite containing marble powder by-product: Substitution and intergrinding methods

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***Abstract:*** This manuscript reports the effects of substitution and interground of MP on the pH of cement and bending and compressive strengths of mortar composite as well as strength projection of green mortar composite from pH of green cement. It also presents the relationships between pH of cement and strength of mortar composite to compute strength gain from pH of cement. The feature of sample made with MP-cement is examined and compared to those made with pure Portland cement—including bending and compressive strengths at 7 d, 28 d, and 90 d, and pHs of cement. Projection of strength gain from pHs of cement is also discussed, and the numeric equations, the coefficients, and the *r* squares, which are essential elements of the strength projection, are given in the experimental study proficiently. Regularly, this study results indicate that the projection for strength gains of green mortar composite could be computed from pHs of green cement properly.

***Keywords:*** recycling; mechanical properties; physical properties; pH; bending strength; compressive strength; cement; marble by-product; mortar composite; corrosion

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## 1. Introduction & objective

Since compressive strength is a significant primary characteristic for cement based non-resilience construction materials, plenty of much research suggests some equations to compute compressive strength from bending strength for reducing some workloads such as preparations of prism mortar and carrying out bending strength test[1]. As these aforementioned equations need to measure the bending strength, they do reduce no the workloads for laboratory research and in-situ construction application. There is a need for comprehensive study so that these workloads are reduced. Since this research uses hydraulic cement's pH to predict compressive strength gains of hydraulic cements, it also reduces these workloads and recommends a novel method for scientists studying on quality controls for cements containing by-products: i.e., marble powder. On the other hand, the corrosion that consists of chemical process including the flows of electron and ion is another significant characteristic for cement based bearing materials. At active site on the metal, called anodes, iron atom loses electrons and surrounds cement based material as ferrous ions. This process is called a half-cell oxidation reaction. The electron remains in the metal and slides to site called cathode zone, where they combine with water and oxygen in the cement based material. The reaction is called a reduction reaction at the cathode zone. To maintain electrical neutrality, the ferrous ion migrates through the pore water to the cathode site where they combine to form iron hydroxides and/or rust. This initial precipitated hydroxide tends to react further with oxygen to form higher oxide. Increases the rust volume reacts further with dissolved oxygen leads to internal stress within the cement based bearing material that may be sufficient to cause cracking and spalling in bonds between cement paste and construction steel[2,3]. Corrosion of inset metal can be greatly reduced by placing crack-free with low permeability and sufficient cover in cement based material. Decreasing water to cement ratio and use of by-product could provide low-permeability for cement based construction material. By-product also increases the resistivity of cement based material due to reducing the corrosion rate even after it initiates.

However, pH of cement is a key factor for bearing construction material so that corrosion does not effect steel negatively. 12–13 alkalinity level (pH) saves the steel covering like a protective film layer in cement paste. Researches on cement containing by product need to measure the pHs of cement and by product in order to overcome negative corrosion effect aforementioned[4–7]. Marble particle is by-product from productions of marble which is essential material for construction industry. The particle is attractive cementitious material due to their significant chemical compound, but disposal of them is associated with environmental and ecological problem. **Table 1** states the chemical compound. In untreated condition, this MP volume generated is about 2,592,000 tons annualy[8]. The particle finds no application in construction industry. An alternative way is to use marble particle employed in many European countries and Canada and USA as intergrinding and/or substitution material for Portland cement. However, because of the concerns on reduction the cement alkalinity, researches have not preferred this alternative way as the best option. Since MP particle does reduce no this alkalinity, this exacting non-budget research is carried out to more effective explain relationships between pH and strength gain of cement. As explained in this study, the article also presents some important relationships between pHs of cement and compressive strength and bending strength of cement.

Objective of this current experimental study is to present the projection for bending and compressive strength by assisting of cement's pH. Conventional testing methods are the uniaxial bending and compression tests to determine strength gain of cement. Although these kind of destructive testing methods give real results, they are both time–consuming and costly. There is also possible to analyze the cement alkalinity by pH testing method. This pH testing method is not developed for replacing the destructive strength methods entirely, but it can become an alternative method for these destructive strength method as more practical, faster, and inexpensive method. Plus, this study responds some primary questions i.e., which method is more beneficial for research related to cement containing by-product by way of substitution and/or intergrinding? How does the substitution method of MP for cement effect positively pH of cement and strength of cement mortar? How does the intergrinding method of MP with cement clinker effect positively pHs of cement and strength of cement mortar? Are the ratios of substitution and/or intergrinding significant in view of the protection for steel bar from corrosion in in-situ application? If so, how does by-product effect pHs of cement and strength of cement mortar? Do some relationships establish between the pHs of cement and strength of cement mortar? If so, are these relationships meaningful?

## 2. Experimental procedure

### 2.1. Materials

In–situ studies use four different types of mortar. First is an ordinary lime based mortar made of a mixture of standard sand, water and quicklime, either in the form of hydraulic lime or non-hydraulic lime[9–11]. Second is cement based mortar is known following the invention of hydraulic Portland cement. Cement mortar composite displays a faster setting time and is known to have a high mechanical strength and low level of porosity in comparison to lime mortar[9–12]. Third is cement-lime mortar composite is made of a proportioned mixture of lime, Portland cement, standard sand and water. Cement-lime mortar composite has such some benefits as the workability, deformation capacity and autogenous healing ability of a lime mortar, and also having the bond quality and compressive strength of a hydraulic cement mortar[11,13]. ASTM presents the rigid categorizations for cement-lime mortars into five different groups according to their mix proportions by volume[14]. Last one is lime-pozzolan mortar composite made of a lime mortar that also contains pozzolanic materials. Some reactions between pozzolanic material and lime enhance the mechanical strengths of the mortar, and therefore lime-pozzolan mortar generally exhibits a higher mechanical strength than that of a pure lime mortar[12,15,16]. Difference of this non-budget research from the abovementioned types of mortar composite is that it uses novel cement-by-product mortar composite and by-product-cement that also contain marble powder as latent hydraulic additive in order to explain effectiveness of MP on strength gains of hydraulic mortar composite and pHs of cement. **Table 1** gives the chemical compositions of MP, CEM I 42.5N cement, and CEM I 42.5 clinker[8].

**Table 1.** Chemical compositions of MP, CEM I 42.5N cement, and CEM I 42.5 clinker.

| Chemical compositions (%) | MP | CEM I 42.5N Cement | CEM I 42.5 Clinker |
|---|---|---|---|
| CaO | 53.7 | 63.5 | 65.09 |
| $SiO_2$ | 0.3 | 19.9 | 21.01 |
| $Al_2O_3$ | 0.1 | 5.2 | 5.6 |
| $Fe_2O_3$ | 0.04 | 3.4 | 3.5 |
| MgO | 0.7 | 1.7 | 1.5 |
| $SO_3$ | 0.05 | 2.8 | 0.8 |
| $K_2O$ | 0.01 | 0.7 | 0.8 |
| $Na_2O$ | 0.3 | 0.8 | 0.8 |
| LOI | 44.1 | 0.015 | 0.3 |
| pH | 12.01 | 12.7 | - |

## Preparations of cement and mortar composite

Preparations of cement and mortar composite consist of three stages. First stage is the preparation of MP in order to specify their characteristic properties. Laboratory type ball mill grinds this mineral waste of marble separately at thirty minutes to form fine particle. Second stage is the mixture proportion designs of cement. Group 1 substitutes marble powder for pure Portland cement at the weight percentages of 6-20-21 and 35 and the substituted marble powder-cement (SMP-C) are named as CEMI42.5MP6, CEMI42.5MP20, CEMI42.5MP21 and CEMI42.5MP35. Group 2 uses pure CEMI42.5N cement as reference cement. Moreover, Group 3 intergrinds marble powder, pure Portland cement clinker, and plaster at the percentages of 6 + 89 + 5, 20 + 75 + 5, 21 + 74 + 5 and 35 + 60 + 5 and the interground marble powder-cement (IMP-C) are named as CCEMI42.5MP6, CCEMI42.5MP20, CCEMI42.5MP21, and CCEMI42.5MP35[8]. TS EN 196-1 specifies the change ratios of ground MP for pure Portland cement in order to make appropriate cement proportion (TS EN 196-1 2009). **Table 2** presents groups and cements, percentages of by-product, pure CEMI42.5N cement, and CEM I 42.5 clinker[8].

**Table 2.** Groups and types of cement, proportions of by-product, pure CEMI42.5N cement, CEM I 42.5 clinker, and intergrinding time.

| **Cements** | | **Proportions of By-products, Cements, Clinkers, and Gypsums** | | | | **Intergrinding Time (s)** |
|---|---|---|---|---|---|---|
| **Groups** | **Codes** | **MP** | **CEM I 42.5N** | **CEM I 42.5 Clinker** | **Gypsum** | |
| Group 1 | CEM I 42.5 MP6 | 6 | 94 | 0 | 0 | 0 |
| | CEM I 42.5 MP20 | 20 | 80 | 0 | 0 | 0 |
| | CEM I 42.5 MP21 | 21 | 79 | 0 | 0 | 0 |
| | CEM I 42.5 MP35 | 35 | 65 | 0 | 0 | 0 |
| Group 2 | CEMI42.5 | 0 | 100 | 0 | 0 | 0 |
| Group 3 | CCEM I 42.5 MP6 | 6 | 0 | 89 | 5 | 30 |
| | CCEM I 42.5 MP20 | 20 | 0 | 75 | 5 | 30 |
| | CCEM I 42.5 MP21 | 21 | 0 | 74 | 5 | 30 |
| | CCEM I 42.5 MP35 | 35 | 0 | 60 | 5 | 30 |

Last stage deals with preparations of mortar composite containing SMP-C, IMP-C, and reference cement for monitoring strength gain at 7 d, 28 d, and 90 d. In preparation of mortar composite, following procedure uses a medium planetary mixer for 4 (min): (1) add water and SMP-C and/or IMP-C, and/or reference cement into bowl; (2) mix them for 30 (s) at low speed; (3) add CEN standard sand at 30 (s); (4) mix them for 30 (s) at high speed; (5) stop the mixer for 15 (s) to scrape bowl; (6) mix for 60 (s) at high speed; (7) cast each mortar mixes in prism mould (40x40x160 mm) as three layers; (8) collapse each layer 60 times[8,17]. Mortar composite is mixed with water:cement:sand ratio of 1:2:6. **Table 3** presents types of substituted-cement mortar (SCM) composite, reference cement mortar (RCM) composite, interground-cement mortar (ICM) composite, and mixture proportions of the mortar composite for 0.000768 $m^3$[8].

**Table 3.** Types of substituted-cement mortars (SCM), reference cement mortars (RCM), interground-cement mortars (ICM), and mixture proportions of these mortars for one standard 3—gang mould.

| **Types of Mortar** | | **Mixture proportions of cement mortar** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Substituted-Cements** | | **Interground-Cements* (g)** | **Tap water (mL)** | **Sand (g)** | **Water-to-binder ratio** |
| | | **MP (g)** | **CEM I 42.5N (g)** | | | | |
| SCM | SC-MP6M | 27 | 423 | 0 | 225 | 1350 | 0.5 |
| | SC-MP20M | 90 | 360 | 0 | 225 | 1350 | 0.5 |
| | SC-MP21M | 94.5 | 355.5 | 0 | 225 | 1350 | 0.5 |
| | SC-MP35M | 157.5 | 292.5 | 0 | 225 | 1350 | 0.5 |
| RCM | CEMI42.5M | 0 | 450 | 0 | 225 | 1350 | 0.5 |
| ICM | IC-MP6M | 0 | 0 | 450 | 225 | 1350 | 0.5 |
| | IC-MP20M | 0 | 0 | 450 | 225 | 1350 | 0.5 |
| | IC-MP21M | 0 | 0 | 450 | 225 | 1350 | 0.5 |
| | IC-MP35M | 0 | 0 | 450 | 225 | 1350 | 0.5 |

## 2.2. Methods

This research divides methods into two experimental parts and a numerical calculation to explain how the MP effects for strength-related properties of hydraulic mortar composite and pHs of cement.

These three stages include:

- Chemical experiments are carried out for pHs of cement in order to monitor how MP effects the alkaline levels of the cement.
- This study measures some strength gain of mortar containing the aforementioned cement in order for better explaining how MP effects the target strength levels of the cement.
- This article suggests some equations for the projections of strength from pH results.

### 2.2.1. pH experiments of cement

TS 12072 standard method measures the pHs of cement (**Table 2**) by a pH meter having specifications in the TS 5133 standard (TS EN 196-2 2012; TS 12072 1996; TS 5133/T1 1990). Following procedure uses automatic pH meter for measuring pHs of cement: (1) add 10 mL deionized water and 1 (g) cement into beaker; (2) mix the suspension on magnetic stirrer; (3) wait until cement precipitates; (4) wash electrode of pH meter with deionized water; (5) put electrode of pH meter in suspension; (6) record pH of cement based suspension. For each mix, pH meter tests three suspensions. The article presents average values of pH as the descriptive pH of cement. Image of pH meter for measuring of cement alkalinity is seen in **Figure 1**.

**Figure 1.** Image of pH meter for measuring of cement alkalinity.

### 2.2.2. Bending strength experiments of mortar composite

Standard method examines the bending strengths of prism mortar 40 × 40 × 160 (mm) at 7 d, 28 d and 90 d (**Table 3**). This study demolds and cures the prism mortar into water in closet at 22 ± 3 °C and 98% relative humidity until testing. To maintain mortar immersed into curing water, fresh water is added when necessary. For each mix at each age, hydraulic bending machine tests six samples. The article presents average values of sample as the descriptive bending strength for hydraulic mortar composite containing MP (TS EN 196-1 2009). Equipment for mortar composite preparation is seen in **Figure 2**, left to right, the automatic-minute-controlled mixer, the bending moment testing machine, computer controlled water curing cabinet, bending moment testing of mortar composite containing MP.

**Figure 2.** Equipment for preparation and testing of mortar composite, left to right, the automatic-minute-controlled mixer, the bending moment testing machine, curing cabinet whose relative humidity and water temperature is controlled by computer, bending moment testing of mortar composite containing MP.

### 2.2.3. Compressive strength experiments of mortar composite

Standard method specifies compressive strengths of cubic mortar 40 × 40 × 40 (mm) at 7 d, 28 d, and 90 d (**Table 3**) (TS EN 196-1 2009). This non-budget research demolds and cures the cubic mortar into water in closet at 22 ± 3 °C and 98% relative humidity until testing. To maintain mortar immersed into curing water, fresh water is added when necessary. For each mix at each age, hydraulic compression machine tests twelve samples. The article gives average values as the descriptive compressive strength for hydraulic mortar composite containing MP. Equipment for measurement of mortar composite compressive strength is seen in **Figure 3**.

**Figure 3.** Equipment for measurement of mortar composite compressive strength.

## 3. Outcomes and arguments

**Table 4** presents the pHs of cement, bending strengths of mortar composite and compressive strengths of mortar composite at 7 d, 28 d, and 90 d. It also gives the names of cement and of mortar[8].

**Table 4.** The pHs of cement, compressive strengths of mortar, and bending strengths of mortar at 7 d, 28 d, and 90 d, and the types of cement and of mortar.

| Types of Cement | Chemical Properties | Types of Mortars | Mechanical Properties | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Bending Strengths (MPa) | | | Compressive Strengths (MPa) | | |
| | pH | | 7th-d | 28th-d | 90th-d | 7th-d | 28th-d | 90th-d |
| CEM I 42.5 MP6 | 12.51 | SC-MP6M | 6.44 | 6.87 | 6.2 | 39.63 | 45.09 | 39.31 |
| CEM I 42.5 MP20 | 12.51 | SC-MP20M | 5.05 | 5.67 | 5.59 | 31.81 | 40.52 | 32.96 |
| CEM I 42.5 MP21 | 12.49 | SC-MP21M | 4.7 | 5.2 | 4.32 | 28.78 | 33.36 | 30.15 |
| CEM I 42.5 MP35 | 12.46 | SC-MP35M | 4.49 | 4.5 | 4.13 | 22.71 | 24.73 | 22.09 |
| CEM I 42.5N | 12.72 | CEMI42.5M | 5.37 | 6.25 | 5.39 | 34.29 | 43.06 | 44.15 |
| CCEM I 42.5 MP6 | 12.73 | IC-MP6M | 5.4 | 6.26 | 6.37 | 31.76 | 40.72 | 42.61 |
| CCEM I 42.5 MP20 | 12.71 | IC-MP20M | 4.84 | 5.43 | 5.3 | 26.99 | 37.82 | 32.31 |
| CCEM I 42.5 MP21 | 12.77 | IC-MP21M | 4.66 | 5 | 5.13 | 24.61 | 32.52 | 30.26 |
| CCEM I 42.5 MP35 | 12.58 | IC-MP35M | 4.1 | 4.12 | 3.88 | 21.89 | 22.55 | 22.04 |

## 3.1. pHs of cement

Although the natural tendency of construction steel is to undergo corrosion reaction, the alkaline structure of cement (pH of 12 to 13) provides a protective layer for construction steel. With the high pH level, there is a thin oxide layer on the steel. This layer prevents metal atoms from dissolving and stops no corrosion actually, it reduces the corrosion rate in a significant level. For steel in construction, the passive corrosion rate is typically 0.1 (µm) per year. Without the protective film layer, the corrosion of steel is 1000 times higher than steel having protective layer (ACI 222R-01 2001). Because of this inherent protection, reinforcing steel does not corrode in the majority of cement pastes and structures. However, corrosion can rapidly occur when the protective layer is destroyed. The destruction of protective layer occurs since the alkalinity of cement is reduced. **Table 4** states the pHs for cement containing marble powder[8]. Since this study replaces MP with pure Portland cement up to 35%, the cement displays no less pH ratio than 97% of pH of Portland cement. The highest reduction of pH is in CEM I 42.5 MP35 cement with decreasing ratio of 2.1% while the lowest reduction of pH is in CEM I 42.5 MP6 cement with decreasing ratio of 1%. Results imply that the substitution effect of MP leads to reducing for cement's pH without deteriorating its alkaline structure (**Table 4**). The interground-cement also exhibits same effect on pH of cement, similar to the substituted-cement. Since the 35%-MP is added to cement clinker for intergrinding, pH of the cement is no less than 99% of pH of Portland cement. The highest reduction of pH is in CEM I 42.5 MP35 cement with decreasing ratio of 1.2% while the equal pH is in CEM I 42.5 MP6 cement. Results also reveal that this intergrinding effect leads to no reduction for alkaline structure of cement since MP is added up to 6% (**Table 4**).

## 3.2. pH-assisted projection for bending strengths of mortar composite

**Table 4** presents the bending strengths at 7 d, 28 d, and 90 d for mortar prepared with SMP-C, IMP-C, and reference cement[8]. Following figures illustrate some relationships between pHs of cements and bending strengths of mortars. They also present differences in equations specified for substitution and intergrinding of by-product. Since cement–based construction material is accepted non-resilience material, author expresses results such as ups–and–downs on bending strengths of mortar. Therefore, effects of microstructure of cement hydration on bending strength gains will not be signified. Increasing of loss on ignition (LOI) and alkali in cement paste also causes the reduced strength gain in hydraulic cement mortar[18–21]. **Figure 4**

specifies two relationships between pHs of cement and 7th-d bending strengths of mortar containing marble powder by way of substitution and intergrinding.

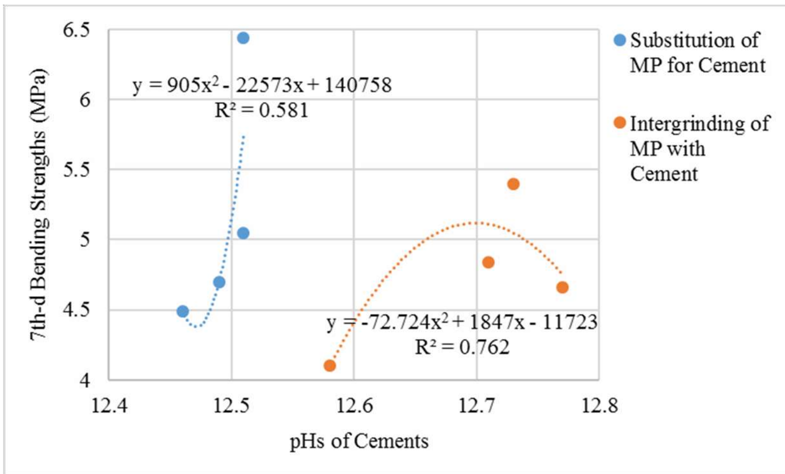


**Figure 4.** Relationships between pHs of cement and 7th-d bending strengths of mortar containing marble powder by way of substitution and intergrinding.

Since this comprehensive study substitutes MP with cement from 6% to 35% (over 5.5 times) in mortar, this substitution leads to the reduction of 4% bending strength at 7 d, except SC-MP6M. These SC-MP6M has over 19% greater bending strength than that of CEMI42.5M at 7 d. This growth explains the mechanism of MP substitution as initial bending strength activator. Plus, bending strengths of MP-SCM are located in a relatively wide range of 4.4–6.4 (MPa) at 7 d. This wide range implies that high substitution ratio of MP for cement causes the reduction for 7th-d bending strengths of hydraulic cement mortar, nevertheless once again, the 6%-MP substitution shows the most pronounced enhancing effect on bending strength gain at 7 d (**Table 4**). Although ball mill intergrounds marble powder and cement clinker together, the mortar prepared with the IMP-C displays over 5% lower bending strength than that of CEMI42.5M and SC-MPs at 7 d, except IC-MP6M. These IC-MP6M also has approximately 0.5% higher bending strength than that of CEMI42.5M mortar at 7 d. In view of these intergrinding of MP with cement clinker, the bending strength locates in a relatively narrow range of 4.1–5.4 (MPa) at 7 d. This narrow range can explain the mechanism of MP intergrinding as stabilizer for hydraulic pure Portland cement system. This narrow range is also the lowest in the mortar containing marble powder by way of intergrinding. This high intergrinding of MP with cement clinker leads to the reduction for bending strength, nevertheless, the 6%-MP blending shows the enhancing effect for 7th-d bending strength gain (**Table 4**). The substitution of MP for cement is more effective than the intergrinding of it with cement clinker in view of 7th-d bending strength. Moreover, **Figure 4** also reveals relationships between pHs of cement and 7th-d bending strength for mortar containing marble powder by way of substitution and intergrinding. This figure gives polynomial equations to show these relationships. **Figure 4** also presents the *R*-squared values show two significant relationships for projection of 7th-d bending strengths of mortar from pHs of cement. They show a good compatibility between two specified properties. As figure exhibits important relationships between pHs of cement and 7th-d bending strength, one may predict a specified strength by testing at least one of the pHs of cement (**Figure 4**). However, these results are in coherence with previous study[18] when considering the changes of chemical composition at 7 d and 28 d and 90 d. Effect of admixture containing high calcium oxide on strength gain deals with fluctuation of silicon oxide ($SiO_2$), sodium oxide ($Na_2O$), and alkali as well as increasing of LOI[22]. This knowledge implies that more than 6% of admixture containing high calcium oxide has no positive effect on early bending strength gains of mortar[20,21]. Moreover, these results are in coherence with previous study when considering the changes of chemical composition at 7 d and 28 d and 90 d. Blending of artificial pozzolan accelerates the tendency of strength gain at later ages because it reduces the LOI in the cement. Mortar containing up to 35% artificial pozzolan displays a greater 28th-d bending strength than that of 7 d[21,22]. **Figure 5** reveals relationships between pHs of cement and 28th-d bending strength for mortar containing marble powder by way of substitution and intergrinding.

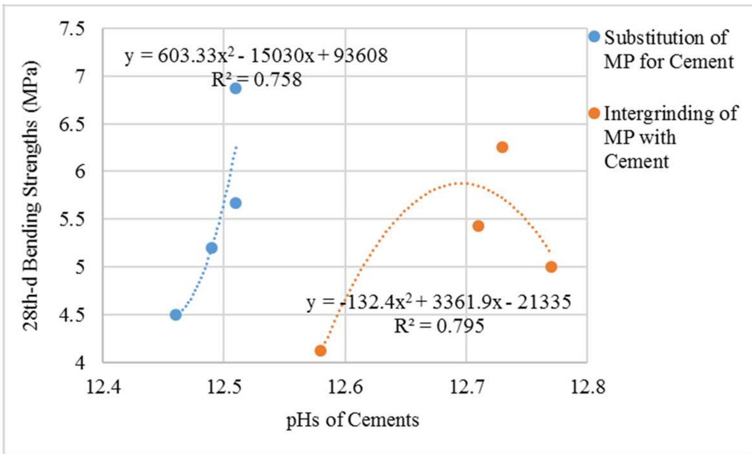


**Figure 5.** Relationships between pHs of cement and 28th-d bending strengths of mortar containing marble powder by way of substitution and intergrinding.

Since this study substitutes MP with cement up to 35% (over 5.5 times) in mortar, this substitution leads to the reduction of 12% for bending strength at 28 d, except SC-MP6M. The SC-MP6M has over 9% greater 28th-d bending strength than that of CEMI42.5M. Plus, bending strength of SMP-C mortar at 28 d is located in a relatively wide range of 4.5–6.8 (MPa). Once again, this wide range indicates that high substitution ratio of MP for cement causes the reduction for 28th-d bending strength of hydraulic cement mortar. These results also reveal that the 6%-MP substitution shows a pronounced enhancing effect on bending strength gain at 28 d (**Table 4**). Although marble powder and cement clinker are interground, the mortar prepared with the IMP-C displays over 20% lower 28th-d bending strength than that of CEMI42.5M, except IC-MP6M. The IC-MP6M also has approximately 0.5% higher 28th-d bending strength than that of CEMI42.5M. In view of the intergrinding of marble powder with cement clinker, the bending strength is located in a relatively wide range of 4.1–6.2 (MPa) at 28 d. This wide range implies that high substitution ratio of MP for cement causes the reduction for 28th-d bending strength of hydraulic cement mortar. The strength value is the lowest in the mortar containing marble powder. This high intergrinding of MP with cement clinker leads to the reduction for 28th-d bending strengths, nevertheless, the 6%-MP blending provides an enhancing effect for 28th-d bending strength gain (**Table 4**). The substitution of MP for cement is more effective than the intergrinding of it with cement clinker in view of 28th-d bending strength. Moreover, **Figure 5** shows two meaningful relationships for projection of 28th-d bending strength of mortar from pH of cement. Polynomial equations are placed on this figure to show these relationships. **Figure 5** also presents the *R*-squared values. They show a good compatibility between two specified properties. As figure exhibits influential relationships between pH of cement and 28th-d bending strength, one may predict a specified strength by testing at least one of the pH of cement (**Figure 5**). However, these results are in coherence with previous study[18–20] when considering the chemical composition change at 7 d and 28 d and 90 d. Chemical composition change of cement paste explains the mechanism of admixture containing high calcium oxide. Blending of high calcium oxide based admixture provides to continue the strength gain in mortar after 28 d since it activates hydrations of calcium based compounds in cement pastes[18,21]. Moreover, data obtained from current research on mortar containing fly ash[18,20] reveals that there are at least two mechanisms on early strength gain of Portland pulverized fly ash cement (PPFA-C) containing nano graphite particle (nG). First, the nG could open between cement particles to provide proper dispersion of fly ash for the nucleation and growth of hydration product of the calcium carbon hydroxide (C–C–H). In this case, well-dispersed nG particle accelerates the initial strength gains for PPFA-C[18,20]. Following paragraphs will explain the second mechanism. **Figure 6** reveals relationships between pH of cement and 90th-d bending strength of mortar containing marble powder by way of substitution and intergrinding.

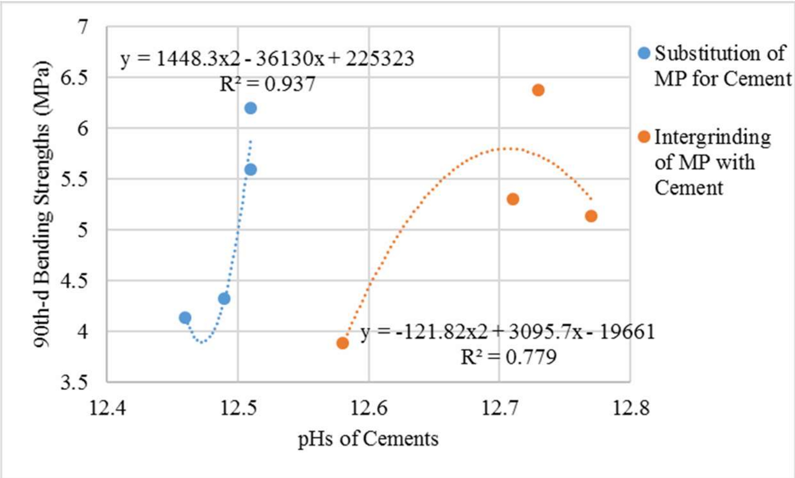


**Figure 6.** Relationships between pHs of cement and 90th-d bending strengths of mortar containing marble powder by way of substitution and intergrinding.

Since MP is substituted for cement from 6% to 35% (over 5.5 times) in mortar, this substitution leads to the reduction of 6% for bending strength at 90 d, except SC-MP6M. This SC-MP6M has over 15% greater 28th-d bending strength than that of CEMI42.5M. Plus, 90th-d bending strength of SMP-C mortar is located in a relatively wide range of 4.1–6.2 (MPa). This wide range points that the low substitution of MP provides strength gain for hydraulic cement at later age. These results also imply that high substitution ratio of MP for cement causes the reduction for 90th-d bending strength of SMP-C mortar, nevertheless once again, the 6%-MP substitution shows a pronounced enhancing effect on bending strength gains at 90 d (**Table 4**). Although marble powder and cement clinker are interground, the mortar prepared with the IMP-C displays over 4% lower bending strength than that of CEMI42.5M at 90 d, except IC-MP6M. The IC-MP6M also has over 18% higher bending strength than that of CEMI42.5M at 90 d. In view of the intergrinding of marble powder with cement clinker, the bending strength is located in a relatively wide range of 3.8–6.3 (MPa) at 90 d. This wide range points that the low intergrinding of MP provides strength gain for hydraulic cement at later age. This high intergrinding of MP with cement clinker also leads to the reduction for bending strength, nevertheless once again, the 6%-MP blending shows an enhancing effect for 90th-d bending strength gains (**Table 4**). The substitution effect of MP for cement is similar to the intergrinding effect of MP with cement clinker in view of 90th-d bending strength. Moreover, **Figure 6** shows two relationships for projection of 90th-d bending strength of mortar from pH of cement. Polynomial equations are placed on this figure to show these relationships. **Figure 6** presents the *R*-squared values. They show a good compatibility between two specified properties. As figure exhibits significant relationships between pH of cement and 90th-d bending strength, one may predict a specified strength by testing at least one of the pH of cement (**Figure 6**). In addition to the first mechanism aforementioned, the nG particle could potentially provide an additional source of carbon for activation of calcium oxide in cement hydration. Since cement consists of 65% calcium oxide (CaO) content, the rest of 35% cement oxides is not enough to saturate this CaO content, during cement hydration for gaining of hardness and strength. Therefore, the nG particle may produce the calcium carbon oxide (CaCO) as the nG particle can combine with free 30%-CaO content in cement[18,20,22].

### 3.3. pH-assisted projections for compressive strengths of mortar composites

**Table 4** presents the compressive strengths at 7 d, 28 d, and 90 d for mortar prepared with SMP-C, IMP-C, and reference cement. Following figures illustrate some important relationships between pH of cement and compressive strength for mortar containing marble powder by way of substitution and intergrinding. They also present differences in equations specified for substitution and intergrinding of by-product. **Figure 7** specifies relationships between pH of cement and 7th-d compressive strength of mortar containing marble powder by way of substitution and intergrinding

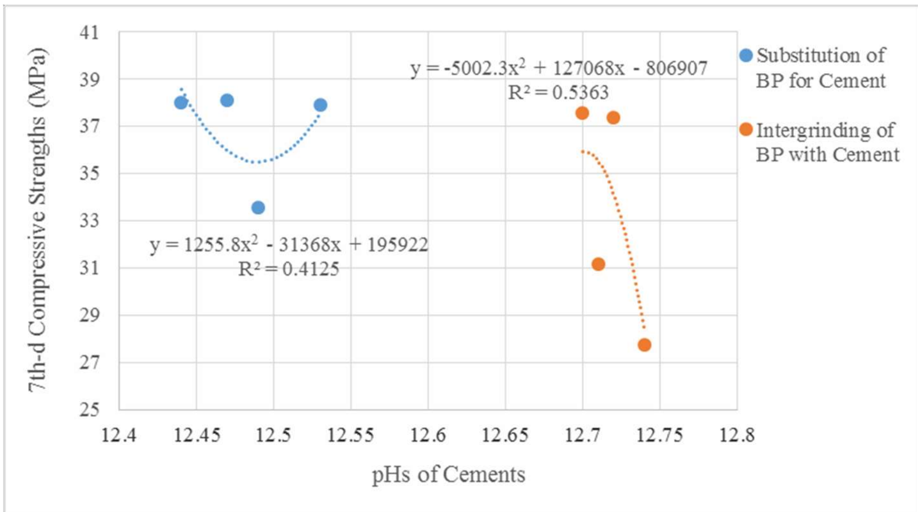


**Figure 7.** Relationships between pHs of cement and 7th-d compressive strengths of mortar containing marble powder by way of substitution and intergrinding.

Since MP is substituted for cement from 6% to 35% (over 5.5 times) in mortar, this substitution leads to the reduction of 11% compressive strength at 7 d, except SC-MP6M. The SC-MP6M also has over 15% greater compressive strengths than that of CEMI42.5M at 7 d. Plus, compressive strength of SMP-C mortar is located in a relatively wide range of 22.7–39.6 (MPa) at 7 d. This wide range implies that high substitution ratio of MP for cement causes the reduction for 7th-d compressive strength of hydraulic cement mortar, nevertheless, the 6%-MP substitution shows the most pronounced enhancing effect on compressive strength gain at 7 d (**Table 4**). Although marble powder and cement clinker are interground, the mortar prepared with the IMP-C displays over 23% lower compressive strength than that of CEMI42.5M at 7 d. In view of the intergrinding of marble powder with cement clinker, the compressive strength is located in a relatively narrow range of 21.8–31.7 (MPa) at 7 d. This narrow range can explain the mechanism of MP intergrinding as stabilizer for hydraulic cement. This narrow range is the lowest in the mortar containing marble powder at 7 d. This high intergrinding of MP with cement clinker leads to the reduction for compressive strength (**Table 4**). The substitution of MP for cement is more effective than the intergrinding of it with cement clinker in view of 7th-d compressive strength. Moreover, **Figure 7** also shows two relationships for projection of 7th-d compressive strength of mortar from pH of cement. Polynomial equations are placed on this figure to show these relationships. **Figure 7** also presents the *R*-squared values. They show a good compatibility between two specified properties. As figure exhibits prominent relationships between pH of cement and 7th-d compressive strength, one may predict a specified strength by testing at least one of the pH of cement (**Figure 7**). However, compressive strength of mortar containing high calcium oxide based admixture is notably lower than that of pure Portland cement based mortar. This can be explained by the increasing of calcium-to-silicon (Ca/Si) ratio from 1.76 up to 2.8[18–22]. On the contrary to the aforementioned scientific fact, compressive strength is the greatest in the mortar containing artificial pozzolan. This can be explained by the increase of silicon-to-calcium (Si/Ca) ratio, from 0.53 up to 0.96[18,19,21]. **Figure 8** reveals relationships between pH of cement and 28th-d compressive strength for mortar containing marble powder by way of substitution and intergrinding.

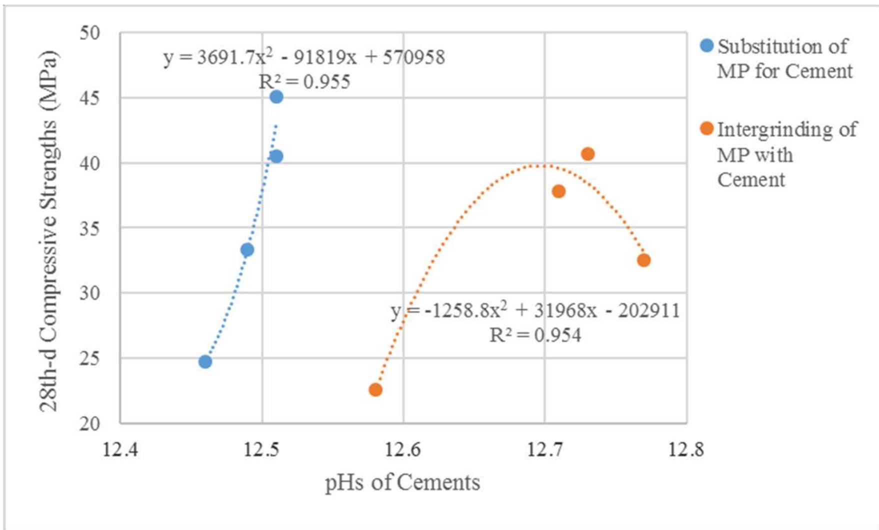


**Figure 8.** Relationships between pHs of cement and 28th-d compressive strengths of mortar containing marble powder by way of substitution and intergrinding.

Since MP is substituted for cement up to 35% (over 5.5 times) in mortars, this substitution leads to the reduction of 22% compressive strength at 28 d, except SC-MP6M. The SC-MP6M has over 4% greater 28th-d compressive strength when compared to CEMI42.5M. Plus, compressive strength of SMP-C mortar is located in a relatively wide range of 24.7–45 (MPa) at 28 d. This wide range reveals that by-products having high CaO content reduce compressive strength of hydraulic cement. These results also imply that high substitution ratio of MP for cement causes the reduction for 28th-d compressive strength gain of SMP-C mortar, nevertheless, the substitution of 6%-MP for cement shows the enhancing effect for 28th-d compressive strength gain (**Table 4**). Although marble powder and cement clinker are interground, the mortar prepared with these IMP-C displays over 30% lower 28th-d compressive strength than that of CEMI42.5M mortar at 28 d. In view of the intergrinding of marble powder with cement clinker, the compressive strength is located in a relatively wide range of 22.5–40.7 (MPa) at 28 d. This wide range explains the non-resilience structure of hydraulic cement. These strength values are the lowest in the mortar containing marble powder at 28 d. This high intergrinding of MP with cement clinker leads to the reduction for 28th-dcompressive strength (**Table 4**). The substitution of MP for cement is more effective than the intergrinding of it with cement clinker in view of 28th-d compressive strength. Moreover, **Figure 8** shows two important relationships for projections of 28th-d compressive strength of mortar from pH of cement. Polynomial equations are placed on this figure to show these relationships. **Figure 8** also presents the *R*-squared values. They show a good compatibility between two specified properties. As figure exhibits meaningful relationships between pH of cement and 28th-d compressive strength, one may predict a specified strength by testing at least one of the pH of cement (**Figure 8**). However, blending of artificial pozzolan accelerates the tendency of strength gain at later ages because it reduces the LOI in the cement paste. Up to 35% artificial pozzolan displays the greatest compressive strength and bending strength in the mortar[18,19,21]. Moreover, effects of artificial pozzolan on strength gain deals with increasing of $SiO_2$ in cement paste. Average of $SiO_2$ tends to increase in cement paste continuously. Strength gain in mortar containing artificial pozzolan acts similar to $SiO_2$ in the cement paste. Since mortar containing artificial pozzolan achieves nearly 52.5 (MPa) compressive strength at 90 d, blending up to 35% artificial pozzolan has a positive effect on strength gain of cement mortar at later age[18–21]. **Figure 9** reveals relationships between pH of cement and 90th-d compressive strength for mortar containing marble powder by way of substitution and intergrinding.

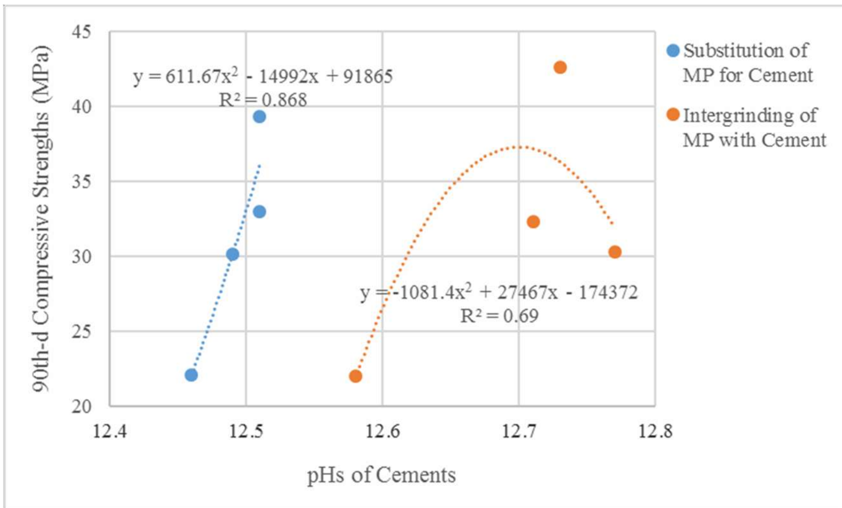


**Figure 9.** Relationships between pHs of cement and 90th-d compressive strengths of mortar containing marble powder by way of substitution and intergrinding.

Since MP is substituted for cement up to 35% (over 5.5 times) in mortar, this substitution leads to the reduction of 42% compressive strength at 90 d. Plus, compressive strength of SMP-C mortar is located in a relatively wide range of 22–39.3 (MPa) at 90 d. As 90th-d compressive strength of SMP-C mortar is lower than that of 28th-d compressive strength of SMP-C mortar, these result reveals that by-product having high CaO content reduces compressive strength of cement, more than over 50%. The results also imply that high substitution ratio of MP for cement causes the reduction for 90th-d compressive strength gain of SMP-C mortar and hence, the substitution of MP for cement shows the most pronounced enhancing effect on initial compressive strength gain (**Table 4**). Although marble powder and cement clinker are interground, the mortar prepared with these IMP-C displays over 38% lower compressive strength than that of CEMI42.5M mortar at 90 d. In view of these intergrinding of marble powder with cement clinker, the compressive strength is located in a relatively wide range of 21.8–31.7 (MPa) at 90 d. This wide range indicates that the MP as intergrinding constituent provides a non-resilience for compressive strength gain of hydraulic cement. The values are the lowest in the IMP-C mortar at 90 d. This high intergrinding of MP with cement clinker also leads to the reduction for compressive strength (**Table 4**). The substitution effect of MP for cement is similar to the intergrinding effect of it in view of 90th-d compressive strength. Moreover, **Figure 9** shows two influential relationships for projection of 90th-d compressive strength of mortar from pH of cement. Polynomial equations are placed on this figure to show these relationships. **Figure 9** also presents the *R*-squared values. They show a good compatibility between two specified properties. As figure exhibits significant relationships between pH of cement and 90th-d compressive strength, one may predict a specified strength by testing at least one of the pH of cement (**Figure 9**). However, in the pure Portland cement, where the $Ca(OH)_2$ content is greatest when compared to all other cement combinations, the strength gain would depend on the formation of other hydration products, most probably ettringite and calcium-silicon-hydrates

(C–S–H) and calcium-alumina-hydrates (C–A–H) and calcium hydrates ($Ca(OH)_2$)[18,19,21]. Moreover, the results are in coherence with previous study[18–22] when considering the chemical composition change at 7 d and 28 d and 90 d. The chemical composition change of cement paste explains mechanism of admixture containing artificial pozzolan on strength gain. Blending of it provides to continue the strength gain of mortar up to 90th-d since it activates hydrations of silica based compound in cement paste. Therefore, it tends to be activator for strength gain of mortar at later age. In high blending ratio of artificial pozzolan, the increasing ratios of strength gain are greater than that of strength gain of pure Portland cement mortar.

## 4. Inferences and suggestions

This comprehensive non-budget research presents novel insight between pH of cement and strength gain of mortar in view of corrosion and strength gain projection. Chemical compound of MP such as oxide compounds, LOI, and pH, offers advantages for pure Portland cement. Furthermore, the use of MP as substitution and intergrinding constituent in pure Portland cement saves existing resources of natural raw materials. Economic and environmental benefit by reducing $CO_2$ emission is well established in literature.

However, the experimented properties confirm that the MP enhances the strength gain of mortar as well as pH of cement in specific cement mixture. Cement mixture prepared with MP, pure Portland cement, and/or cement clinker meets the required strength gain of standard mortar as well as pH of cement for saving the inset metal from corrosion. However, results present substantial relationships, equations, coefficients, and r squares between strength gain of mortar and pH of cement to project strength gain from pH of cement. Additionally, MP can be described as initial strength gain accelerator. In view of inferences, this study could suggest to use MP particle by-product as prepared in this research method for the large scale productions of substituted-cement and intergrinding-cement.

## Conflict of interest

The author declares no conflict of interest.

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