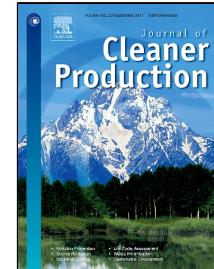


# Accepted Manuscript

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PII: S0959-6526(17)31769-9

DOI: 10.1016/j.jclepro.2017.08.049

Reference: JCLP 10307

To appear in: *Journal of Cleaner Production*

Received Date: 02 May 2017

Revised Date: 28 June 2017

Accepted Date: 06 August 2017

Please cite this article as: Alaa M. Rashad, Phosphogypsum as a construction material, *Journal of Cleaner Production* (2017), doi: 10.1016/j.jclepro.2017.08.049

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**Phosphogypsum as a construction material****Alaa M. Rashad<sup>1</sup>**

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**Abstract:** Phosphogypsum (PG) is a by-product from the industry of phosphate fertilizer. Approximately 4-6 tonnes of PG are generated per tonne of phosphoric acid production. The continuous growth in **the** world population increases food production demand which requires an increase in phosphate fertilizer production resulting in an increase in PG content. Approximately 85% of this by-product is still discarded into the ocean or river, or stored in ponds or leaps without purification. This disposal causes serious contamination. Reduction in the disposal of this by-product has economic and environmental benefits. Extensive investigations have been carried out to reuse PG in different fields such as soil stabilization amendments, agricultural fertilizers, set controller in cement manufactures and building materials. This paper reviews the earlier studies which reused PG as a construction material. The effect of PG on some properties of the matrix such as workability, unit weight, mechanical strength and durability has been reviewed and discussed. The outcome of this review should place a base for the future investigations and uses of PG in sustainable methods.

**Keywords:** Phosphogypsum, Purification, Fresh **properties**, Hardened **properties**.

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## 1. Introduction

Phosphogypsum (PG) is a by-product generated from the phosphorus fertilizer industry (phosphoric acid production). PG is similar to natural gypsum, but there are some differences, of which it contains some impurities such as water-soluble phosphate ( $P_2O_5$ ), water-soluble fluoride ( $F^-$ ) and  $P_2O_5$  substituted in the gypsum crystal lattice. PG and gypsum are both calcium sulfate dihydrate. The name of PG is used to label the by-product of wet-process phosphoric acid production, whilst gypsum denotes to the natural mineral. PG consists mainly of calcium sulfate dehydrate ( $CaSO_4 \cdot 2H_2O$ ), making up over 90% of it, in association with various amounts of silicon,  $F^-$ ,  $P_2O_5$  and organic substances (Rashad, 2015). PG contains appreciable amounts of radium-226, uranium and other uranium decay products (IAEA, 2013). The major chemical elemental composition of PG varying according to the type of phosphoric acid process used, of which the content of CaO fluctuated from 32.2% to 36.9% and the content of  $SO_3$  fluctuated from 44% to 50.3% (Rutherford et al., 1994). Table 1 shows the oxide composition of PG for different studies. PG consists primarily of silt size. The maximum particle size of dehydrate PG (resulting from wet process) varying from 0.5 mm to 1.0 mm and typically 50-75% passes through 0.075 mm screen. Hemihydrate PG (resulting from dry process), in most cases, has a larger particle size than dehydrate form. The moisture content is usually fluctuated from 8% to 30%. The PG maximum density can be obtained when moisture content fluctuated from 15% to 20% (IAEA, 2013). PG is a moist gray (Fig. 1), powdery, its bulk density fluctuated from 0.9 to 1.7 g/cm<sup>3</sup>. PG is highly acidic (pH value around 1) when initially stored, relevant to residual acid, but this acidity is progressively decreased by dewatering and weathering (Hentati et al., 2015) and

reached 2.5-6 (IAEA, 2013). PG particle density fluctuated from 2.27 to 2.4 g/cm<sup>3</sup>, whilst its bulk density fluctuated from 0.9 to 1.7 g/cm<sup>3</sup> (Rutherford et al., 1994).

The phosphate is available in many countries, Fig. 2 shows the 15 top phosphate-producing countries (Mineral, 2016). An industrial plant of phosphate fertilizers originates approximately 4-6 tonnes of PG for every tonne of phosphoric acid produced. The total amount of PG produced up to 2006 was estimated to be around 6 billion tonnes (IAEA, 2013). In 1980, the worldwide production of PG was in the range of 120-150 million tonnes (Rutherford et al., 1994). The annual production of PG worldwide was estimated to be around 160 million tonnes. Production is increasing worldwide and could reach 200-250 million tonnes within the next decade or two (IAEA, 2013). The major part of PG is still disposed in large stockpiles and into water bodies resulting in serious environmental contamination **of soil, water and atmosphere** (Tayidi et al., 2009). This contamination may occur from radon gas, atmospheric contamination with F<sup>-</sup>, groundwater pollution with radionuclides, acidity or mobile anions, radioactive dust inhalation, direct exposure to radiation and water seepage during the long-term downward leaching (Rutherford et al., 1994). So that reuse **of** PG is very important issue. Already about 15% of the world PG production is reused in different fields such as soil stabilization amendments, agricultural fertilizers, set controller in cement manufactures and building materials. This paper reviews the earlier studies which reused PG as a construction material. The effect of PG on some properties of the matrix such as workability, unit weight, mechanical strength and durability has been reviewed and discussed. The outcome of this review should place a base for the future investigations and uses of PG in sustainable methods.

## 2. Toxicity and purification

PG contains impurities of phosphates, free phosphoric acid, organic matter and fluorides. PG also contains some of radioactive elements such as Ra<sup>226</sup>, Pb<sup>210</sup>, Po<sup>210</sup>, U<sup>238</sup> and U<sup>234</sup> which are derived from phosphate rocks (Singh, 2002). Bolivar et al. (2000) depicted that 90% of Po and Ra initially presented in phosphate rock remained in PG, whilst the remaining U percentage was lower than 20%. In spite of PG contains these contaminations, it could not be classified as a toxic waste because it was not corrosive and the average total elemental concentration of elements categorized as toxic (Ba, As, Cr, Cd, Hg, Pb, Se and Ag) by the Environmental Protection Agency (EPA) were lower than the EPA allowable toxic elemental criteria for toxic hazardous waste (Rutherford et al., 1994). Campos et al. (2017) depicted that recycling PG as a building material is a safe practice, of which no further health risk from the radiological point of view. Li et al. (2017) measured the pollution of PG before and after its inclusion into cementitious paste backfill (PG/cementitious ratio was 4/1). They concluded that when PG was incorporated into backfill samples, the release of F, P and metals as well as the risk of diffusion of pollutants were significantly decreased.

The main shortage to the commercial use of PG is the presence of these radioactive elements and impurities, of which they prolonged the setting time and declined the mechanical strength. Trials are being conducted to remove or at least reduce these impurities from raw PG to guarantee its safe use in the construction field. Tayidi et al. (2009) depicted that PG treatment methods mentioned in the earlier studies can be classified as methods including chemical or physical treatments and methods including thermal treatments. So that researchers used different methods to

eliminate the impurities from raw PG such as washing, wet sieving, treatment with a mixture of silica and sulphuric acid or hot aqueous ammonium sulfate solutions, neutralization with lime and thermally treatments. Aly and Mohammed (1999) removed fluoride and lanthanide from PG with  $\text{HNO}_3$  as well as  $\text{NaNO}_3$  coupled with tributylphosphate. Koopman and Witkamp (2002) depicted that 90% of the heavy metals and lanthanides found in PG can be removed by using a combination of recrystallization and the application of either exchange or membrane technology. El-Didamony et al. (2012) depicted that approximately 76.4%, 71.1%, 75.7% and 62.4% of  $\text{Pb}^{210}$ ,  $\text{Ra}^{226}$ ,  $\text{K}^{40}$  and  $\text{U}^{238}$ , respectively, can be removed from PG by using suitable organic extractants. Singh et al. (1993) shook PG samples with 5-20% aqueous ammonium hydroxide for 24 h at 35 °C. Then the samples were filtered, washed firstly with 0.5% ammonium hydroxide solution then washed with water and finally dried at 42 °C. The results showed a reduction in all impurities by using this method. Singh et al. (1996) eliminated the impurities in PG by wet sieving through 300 µm, washing and drying at 42 °C. Singh (2002) eliminated the impurities of PG by shaking it with 2-5% aqueous citric acid solution for 15-25 min at 30 °C in mechanical shaker. The new product was washed with 0.5-1% aqueous citric acid solution then washed with water and dried. Ölmez and Erdem (1989) refined PG by washing with water, by milk of lime and washing with milk of lime for 5 min at 20 °C after calcination at various temperatures. Mun et al. (2007) used 0.5% milk of lime at 20 °C to wash raw PG for 5 min. The ratio of PG/milk was 14%. Afterward neutralization treatment, PG was dried at 80 °C. van der Merwe and Strydom (2004) stirred PG in sulphuric acid for 30 min at room temperature, at a solid/liquid ratio of 1/4. The composites were then filtered and washed with a saturated milk of lime solution and deionized water, then dried at 45 °C. They also used a combined thermal treatment and sulphuric acid,

of which the sulphuric acid stage was combined with a previously thermal treated PG at 160 °C until constant mass was obtained. Al-Hwaiti (2015) used different methods for treating PG such as lime water + seawater, lime water + tap water, lime water + distilled water, 5% sulphuric acid + seawater, 5% sulphuric acid + tap water, 5% sulphuric acid + limewater, 5% H<sub>2</sub>SO<sub>4</sub> + 2% HNO<sub>3</sub> + distilled water, tap water, distilled water and CaCO<sub>3</sub> powder. Potgieter et al. (2003) eliminated the impurities from PG using different methods such as using milk of lime, 1% HCl wash, 1% H<sub>2</sub>SO<sub>4</sub> wash, 5% Na<sub>4</sub>OH wash, 10% NH<sub>4</sub>OH wash.

There are a lot of studies which tried to eliminate the impurities in PG by calcination, of which Garg et al. (2016) calcined PG at 150-160 °C for 4 h. Singh (1982) calcined PG (size 150 µm) at 160 °C for 4-5 h. Yang and Qian (2011) calcined PG at 500 °C for 4 h. Singh and Garg (1995) calcined PG (fineness 350 m<sup>2</sup>/kg) at 750 °C for 4 h. Taher (2007) calcined Egyptian PG (size < 90 µm) at temperatures of 200, 400, 600 and 800 °C, with a rate of 10 °C/min for 2 h. The results depicted that the optimum calcination temperature was 600 °C, whilst calcination temperatures of 400, 200 and 800 °C came in the second, third and fourth place, respectively. Singh et al. (1990) calcined PG at 800 °C for 4 h. Rashad (2015) calcined PG at 850 °C for 2 h. Leškevičiene and Nizevičiene (2014) calcined PG at 800 and 900 °C for 30 min. Smadi et al. (1999) calcined PG at temperatures of 170, 600, 750, 850 and 950 °C for 3 h. They found the optimum calcination temperatures was in the range of 650-950 °C. Singh and Garg (2000) calcined PG at temperatures ranging from 500-1000 °C with a step of 100 °C. The results depicted an increase in the pH value, specific gravity, specific surface area and density of PG with the increase in calcination temperature, whilst the loss on ignition was decreased.

The recorded studies in this section reveal that there are many ways to reduce, eliminate and remove impurities from PG. The purification of PG may increase the cost of preparing this by-product as a construction material. Reijnders (2007) depicted that the cleanup PG often leads to increasing private costs. Lower private costs have led to interruption of processes producing PG with declined levels of minor components. However, the extraction of lanthanides from some varieties of PG did not increase the private costs. On the other hand, van der Merwe and Strydom (2004) depicted that producing PG with few or no impurities may not be cost effective. Indeed, there are missed information about the costs of using different purification methods required to purify PG compared to those without purification. So that new studies are required to cover this point.

### **3. Workability**

Bhaduria et al. (2006) and Bagade and Satone (2012) depicted a declination in the workability of concrete mixtures with including 5-20% PG as cement substitution. Yang et al. (2016) prepared self-leveling mortar mixture containing 20% cement, 40% PG and 40% natural sand. The natural sand was partially replaced with 5%, 10% and 15% PG. (size 1.6-208.9  $\mu\text{m}$ ). The results depicted a declination in the initial workability with including PG. This declination was increased with increasing PG content. The declination in the workability could be relevant to the higher specific surface area of PG in comparison with natural sand. On the other hand, after 20 min, the workability increased with including 40-50% PG, then declined with including 55% PG. The higher workability could be relevant to the interaction of morphology and setting-retarded of PG, whilst the lower workability could be relevant to the higher specific surface area of PG. Huang et al. (2016) prepared concrete mixture

from 45% pretreated PG (surface area 281.9 m<sup>2</sup>/kg), 49% slag, 2% steel slag, 4% clinker as well as aggregates. The results showed lower workability of PG concrete mixture in comparison with Portland cement concrete one. The declination in the slump height was 36.36%. [Buhari and Raju \(2016\)](#) depicted a declination in the concrete mixtures workability with including 5%, 7.5%, 10%, 12.5% and 15% PG as cement substitution. [Sindhuja et al. \(2016\)](#) depicted a declination in the workability of concrete mixtures with including 10%, 20% and 30% PG as cement substitution. This declination was increased with [increasing](#) PG content. [Srinivasulu and Raghava \(2017\)](#) depicted higher workability of concrete mixtures with including 2.5% and 5% PG as cement substitution, whilst [higher than replacement level of 5%](#) (at 7.5% and 10% PG) [caused a gradually declination in the workability.](#)

The recorded studies in this section reveal a declination in the workability with including PG. This declination was increased with increasing PG content. The declination in the workability could be relevant to the low density of PG compared to [those of](#) natural sand or cement. The declination in the workability with including PG in the mixture can be considered as one of the defects of using this material. Whatever, this problem can be solved by using chemical admixtures.

#### **4. Setting time**

[Shen et al. \(2014\)](#) manufactured calcium sulphaaluminate cement with including different PG contents. They noted that the introduction of PG prolonged the setting time. When 17% PG was used, the initial and final setting time was prolonged by 147.37% and 53.5%, respectively, compared to those containing 18% natural gypsum. [Singh \(2002\)](#) manufactured cement by either intergrinding clinker with PG or clinker with selenite gypsum. When impure PG (fineness 330 m<sup>2</sup>/kg) was used, the

increment in the initial and final setting time was 216.5% and 96.85%, respectively, whilst including aqueous citric acid treated PG (fineness  $334\text{ m}^2/\text{kg}$ ) led to an increment of 64.56% and 6.3%, respectively. Similar results were obtained by [Singh and Garg \(2002\)](#). [Abdelhadi et al. \(2014\)](#) prepared mortar mixtures from clinker, PG and fine aggregate. Clinker was partially replaced with 2%, 3% and 4% PG. PG was dried at  $60\text{ }^\circ\text{C}$  or  $120\text{ }^\circ\text{C}$ . The setting time of these mixtures was compared to those of traditional cement mortar one. For PG dried at  $60\text{ }^\circ\text{C}$ , the results depicted longer setting time with including PG. The increment in the initial setting time was 103%, 112.12% and 130.0% with including 2%, 3% and 4% PG, respectively, whilst the increment in the final setting time was 90.7%, 100% and 109.3%, respectively. For PG dried at  $120\text{ }^\circ\text{C}$ , the increment in the initial setting time was 118.2%, 112.12% and 106.1% with including 2%, 3% and 4% PG, respectively, whilst the increment in the final setting time was 104.65%, 100% and 93%, respectively. [Shen et al. \(2012\)](#) incorporated either 5% PG (fineness  $348\text{ m}^2/\text{kg}$ ) or water-washed PG (fineness  $347\text{ m}^2/\text{kg}$ ) with 70% cement clinker and 25% FA. These mixtures were compared to those containing 5% natural gypsum. The results depicted a significant increment in the setting time with including PG, whilst including water-washed PG depicted a marginal increment. [Ölmez and Erdem \(1989\)](#) depicted longer setting time of cement manufactured from 95% clinker and 5% treated PG compared to those manufactured from clinker and natural gypsum. [Taher \(2007\)](#) manufactured slag cement from 54% cement + 40% slag + 6% PG (size  $< 90\text{ }\mu\text{m}$ ). They also used PG after calcination at 200, 400, 600 and  $800\text{ }^\circ\text{C}$  for 2 h. These mixtures were compared to those containing 6% raw gypsum. The results depicted a significant increment in the initial and final setting time with including PG. The introduction of calcined PG declined the initial and final setting time. As the calcination temperature increased the declination in the

setting time increased, but still longer than those containing raw gypsum. Altun and Sert (2004) manufactured cement pastes from clinker with either PG or natural gypsum. Clinker was partially replaced with either PG or natural gypsum at levels ranging from 1% to 12.5%. The results depicted longer initial and final setting time with including PG in comparison with those containing natural gypsum ones. The much longer retarder effect of PG could be relevant to coating cement particles with inactive materials such as fluorides and calcium phosphate during mixing. Mun et al. (2007) washed PG with 0.5% milk of lime at 20 °C for 5 min. The washed PG was dried at 80 °C, then calcined at 450 °C (APG). They blended 91% slag with 8% APG (fineness 430 m<sup>2</sup>/kg) and 1% slacked lime to manufacture non-sintering cement. Then slag was partially replaced with 2%, 4% and 8% APG. The results depicted longer initial and final setting time with including APG compared to Portland cement one.

Bagade and Satone (2012) partially substituted cement in pastes with 5%, 10%, 15% and 20% PG. The results depicted longer setting time with including PG. The initial setting time was prolonged by 283.33%, 516.67%, 716.67% and 866.67% with including 5%, 10%, 15% and 20% PG, respectively, whilst the final setting time was prolonged by 22.44%, 77.55%, 92.24% and 98.98%, respectively. Bhaduria et al. (2006) depicted 300%, 500% and 733% longer initial setting time of cement mixtures with partially replacing cement with 5%, 10% and 15% PG, respectively, whilst the final setting time was prolonged by 21.43%, 76.73% and 92.42%, respectively. Nigade and Bagade (2015) depicted 220%, 442.65%, 597.14%, 722.85% and 728.57% increment in the initial setting time of concrete mixtures with including 5%, 10%, 15%, 20% and 25% PG as cement substitution, respectively, whilst the final setting time was prolonged by 29.8%, 44%, 102.13%, 106.4% and 107.45%, respectively. Huang and Lin (2011) manufactured binder material from 40% PG

(fineness 512 m<sup>2</sup>/kg), 56% slag and 4% cement, then slag was partially replaced with 20% PG. The results depicted longer setting time with **increasing** PG content. The initial and final setting time was prolonged by 9.8% and 6.37%, respectively, with **increasing** PG content from 40% to 60%. [Singh and Garg \(1995\)](#) prepared mixtures from calcined PG (fineness 350 m<sup>2</sup>/kg) and slag with the ratios of 70:24, 65:30, 60:35 and 50:50. Ca(OH)<sub>2</sub> (2-3%), Na<sub>2</sub>SO<sub>4</sub>.10H<sub>2</sub>O (1.5-2%) and FeSO<sub>4</sub>.7H<sub>2</sub>O (1-1.5%) were incorporated in these mixtures. The results depicted longer setting time with **increasing** calcined PG content. Compared to the mixture containing 50% calcined PG, the initial setting time was prolonged by 20.37%, 38.9% and 66.67% with including 60%, 65% and 70% calcined PG, respectively, whilst the final setting time was prolonged by 12.9%, 29% and 61.29%, respectively. [Huang and Lin \(2010\)](#) depicted longer initial setting time with **increasing** PG (fineness 813 m<sup>2</sup>/kg) content from 25% to 35%, 55% and 65% in PG-steel slag-slag-limestone mixtures. The increment in the initial setting time was 1.49%, 12.3% and 17.5% with including 35%, 55% and 65% PG, respectively, compared to those containing 25% PG. On the other hand, the final setting time **was shorted** by 3.9%, 0% and 1.38%, respectively. [Smadi et al. \(1999\)](#) stated that the initial and final setting time of cement paste mixtures was increased with including PG as cement substitution. The initial setting time was prolonged by 160%, 190%, 260% and 480% with including 10%, 20%, 40% and 80% PG as cement substitution, respectively, whilst the final setting time was prolonged by 32%, 68%, 132% and 444%, respectively.

The recorded studies in this section confirm longer initial and final setting time of the mixture with including PG. This increment in setting time was increased with **increasing** PG content. The much longer retarder effect of PG could be relevant to the formation of the protective coatings of calcium fluoride (CaF<sub>2</sub>) and calcium

phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ ) as inactive elements produced by  $\text{PO}_4^{3-}$  and  $\text{F}^-$  on the surface of cement particles through mixing (Singh, 2002). Ölmez and Erdem (1989) depicted that the impurity in PG has a major effect on setting time of cement. The retarder effect of PG can be mitigated by applying suitable treatment methods on the surface of PG particles. By using treated PG, the setting time was **shorted** compared to those untreated one because of the elimination of some impurities such as  $\text{F}^-$ ,  $\text{P}_2\text{O}_5$ , organic matter and alkalis. Furthermore, using calcined PG possessed shorter setting time than those without calcination. This could be relevant to the reduction of water soluble  $\text{P}_2\text{O}_5$  and fluorides ( $\text{NaF}$  and  $\text{Na}_2\text{SiF}_6$ ) found in PG (Taher, 2007). Thus, it is possible to use PG as **a retarder** agent instead of chemical admixture which **already used for this purpose**. This has good economic benefit. The retarder effect of PG can be considered as one benefit of using this by-product material in some applications in civil engineering such as casting in hot weather, casting retaining deep walls, casting mass concrete and repair elements.

## 5. Unit weight

Taher (2007) depicted that slag cement containing 6% PG (size < 90  $\mu\text{m}$ ) exhibited lower bulk density than those containing 6% raw gypsum, whilst using PG after calcination at 200, 400, 600 and 800  $^{\circ}\text{C}$  for 2 h increased the bulk density. The bulk density was **increased** with **increasing** calcination temperature. Bouchhima et al. (2013) depicted that density of bricks manufactured from 60% PG (size 250  $\mu\text{m}$ ), 32% natural sand, 5% cement and natural hydraulic lime accounted 1598  $\text{kg/m}^3$ . Değirmenci and Okucu (2007) prepared binder mixture from FA (90%) and hydrated lime (10%), then FA was partially replaced with PG (fineness 467  $\text{m}^2/\text{kg}$ ) at levels ranging from 10% to 50%. The results depicted a declination in the dry unit weight

with including PG. This declination was increased with **increasing** PG content. The introduction of 50% PG declined the dry unit weight by 17.21%. In another similar investigation, [Değirmenci \(2008\)](#) prepared binder mixture from FA (90%) and hydrated lime (10%), then FA was partially replaced with PG (fineness  $467\text{ m}^2/\text{kg}$ ) at levels ranging from 10% to 50%. The results depicted a declination in the unit weight with including PG. This declination was increased with **increasing** PG content. The introduction of 10% and 50% PG declined the unit weight by 2.18% and 11.75%, respectively. They also used PG after calcination at  $150\text{ }^\circ\text{C}$  for 2 h. The results depicted 0.44% and 11.2% declination in the unit weight with including 10% and 50% calcined PG, respectively.

[Kumar \(2002\)](#) manufactured bricks from 60% FA, 30% lime and 10% calcined PG, then lime was partially replaced with 10% and 20% calcined PG. The results depicted higher density with **increasing** calcined PG content. The density was increased by 2.35% and 2.6% with including 20% and 30% calcined PG compared to those containing 10% PG. [Türket and Aksin \(2012\)](#) manufactured bricks from clay, then clay was partially replaced with PG at levels ranging from 5% to 30%. The results depicted slightly higher unit weight of bricks with **increasing** PG content. The introduction of 5%, 10%, 15%, 20%, 25% and 30% PG caused 0%, 4.24%, 4.24%, 4.85%, 5.45% and 6.1% increment in the unit weight, respectively.

The recorded studies in this section reveal that the introduction of PG in the matrix may decline or increase its unit weight. This depends mostly on the dry density of the material which was replaced with PG. If the density of the replaced material was higher than those of PG, the unit weight of the matrix was declined and vice versa. Whatever, when natural sand or cement was replaced with PG, the unit weight of the matrix was declined, of which PG has lower density than either natural sand or

cement. The declination of the unit weight with including PG can be considered as one benefit of using this by-product material in some applications in civil engineering such as producing lightweight bricks and plasters.

## 6. Mechanical strength

### 6.1 Cements and binders

[Shen et al. \(2014\)](#) manufactured calcium sulphaaluminate cement with including different PG contents. They noted that the introduction of PG declined the compressive strength. When 17% PG was used the 3, 7 and 28 days compressive strength was lower than those containing 18% natural gypsum. [Singh \(2002\)](#) manufactured cement by either intergrinding clinker with PG or clinker with selenite gypsum. When impure PG (fineness 330 m<sup>2</sup>/kg) was used, the declination in the 1, 3, 7 and 28 days compressive strength was 37.5%, 42.86%, 37.5% and 18.48%, respectively, whilst including aqueous citric acid treated PG (fineness 334 m<sup>2</sup>/kg) led to a declination of 6.25%, 25%, 0.71 and 3.53%, respectively. Similar results was obtained by [Singh and Garg \(2002\)](#). [Altun and Sert \(2004\)](#) manufactured cement pastes from clinker coupled with PG. Clinker was partially replaced with PG at levels ranging from 1% to 12.5%. When 3% PG was used, the highest 28 days compressive strength was obtained. Beyond 3% PG, the compressive strength was declined. [Shen et al. \(2012\)](#) incorporated either 5% PG (fineness 348 m<sup>2</sup>/kg) or water-washed treated PG (fineness 347 m<sup>2</sup>/kg) with 70% cement clinker and 25% FA. These mixtures were compared to those containing 5% natural gypsum. The results depicted 12.1% and 10.63% declination in the 3 days flexural strength and compressive strength with including PG, respectively, whilst the 28 days strength was increased by 7.16% and 2.62%, respectively. The introduction of water-washed treated PG enhanced the 3 and

28 days flexural strength by 0.72% and 9.55%, respectively, whilst the compressive strength was increased by 6.58% and 7.1%, respectively. [Taher \(2007\)](#) depicted that slag cement containing 6% PG (size < 90 µm) exhibited lower compressive strength than those containing 6% raw gypsum, whilst using PG after calcination at 200, 400, 600 and 800 °C for 2 h increased the compressive strength. The compressive strength was increased with **increasing** calcination temperature.

[Min et al. \(2008\)](#) calcined PG at 135 °C for 3 h. The calcined PG was added to FA-lime binders at proportions ranging from 5% to 15%. The FA/lime ratios were in the range of 85/15 to 65/35. The results depicted that the addition of calcined PG improved the compressive strength especially at early ages. The introduction of 8% calcined PG to the mixture containing 85% FA coupled with 15% lime increased the compressive strength at ages of 1, 3, 7, 28 and 90 days by 13.75, 5.65, 6.67, 6.38 and 5.1 times greater, respectively, whilst including 8% calcined PG to the mixture containing 65% FA coupled with 35% lime increased it by 11.83, 6.98, 10.97, 11.65 and 12.42 times greater, respectively. This enhancement could be relevant to the formation of ettringite and gypsum caused by calcined PG which accelerated the pozzolanic reaction of FA. [Değirmenci \(2008\)](#) prepared binder mixture from FA (90%) and hydrated lime (10%), then FA was partially replaced with PG (fineness 467 m<sup>2</sup>/kg) at levels ranging from 10% to 50%. The results depicted a significant declination in the 28 days compressive strength with including PG. This declination was increased with **increasing** PG content. For water curing, the compressive strength was declined by about 90% with including 50% PG, whilst about 79% declination was obtained for dry curing. Similar tendency of the results was obtained by [Değirmenci and Okucu \(2007\)](#). They also used PG after calcination at 150 °C for 2 h. The results depicted about 18% enhancement in the compressive strength with

including 50% calcined PG when dry curing was used, whilst ~38% declination was obtained when water curing was used. The lower compressive strength of the specimens cured in water compared to those dry cured could be relevant to the higher expansion and cracks that happened in the specimens cured in water due to sulfate reaction between gypsum and lime. Huang and Lin (2010) depicted lower 3 and 7 days compressive strength and flexural strength with increasing PG (fineness 813 m<sup>2</sup>/kg) content from 25% to 35%, 45%, 55% and 65% in PG-steel slag-slag-limestone mixtures. At age of 28 days, comparable strength of the mixtures containing 35% and 45% PG to those containing 25% was obtained, whilst a significant declination in strength was obtained for those containing 55% and 65% PG.

## 6.2 Mortars

Abdelhadi et al. (2014) prepared mortar mixtures from clinker, PG and fine aggregate. Clinker was partially replaced with 2%, 3% and 4% PG. PG was dried at 60 °C or 120 °C. The compressive strength of these mixtures was compared to those of traditional cement mortar one. For PG dried at 120 °C, the results depicted a declination in the compressive strength with including PG. The introduction of 2% PG caused 26.84%, 5.76% and 7.36% declination in the 2, 7 and 28 days compressive strength, respectively, whilst including 4% PG caused 27.57%, 11.27% and 17.17% declination, respectively. Mun and So (2008) partially replaced cement in mortars with calcined PG at levels of 5%, 7.5%, 10% and 12.5%. The specimens were steam cured at 65 °C for 6 h. the 28 days compressive strength was increased with increasing calcined PG up to 7.5%, then began to show a downward tendency. The introduction of 7.5% calcined PG enhanced the compressive strength by 22-53% (according to the type of PG). Mun et al. (2007) depicted higher compressive strength of mortars

manufactured from 91% slag, 8% APG (fineness 430 m<sup>2</sup>/kg) and 1% slacked lime with increasing APG content up to 12%, then started to decrease. Bhadauria et al. (2006) depicted 35.5%, 7.75% and 4.32% enhancement in the 3, 7 and 28 days compressive strength of mortars with including 5% PG as cement substitution, respectively, whilst including 10% PG declined it by 25.42%, 31.36% and 18.32%, respectively. In such a way, including 15% PG declined the 3, 7 and 28 days compressive strength by 11.63%, 28.45% and 24.23%, respectively. Yang et al. (2016) prepared self-leveling mortar mixture containing 20% cement, 40% PG and 40% natural sand. Natural sand was partially replaced with 5%, 10% and 15% PG. (size 1.6-208.9 μm). The compressive strength and flexural strength results at age of 28 days did not affect with including PG. On the other hand, the bond strength was declined by 16.67% with increasing PG content from 40% to 55%. Smadi et al. (1999) stated a declination in the compressive strength, splitting tensile strength and flexural strength of mortars by replacing cement with PG at levels up to 100%. This declination was increased with increasing PG content. When air curing was used, the 28 days compressive strength was declined by 10% and 53% with including 10% and 80% PG, respectively, whilst the flexural strength was declined by 14% and 87%, respectively, and the tensile strength was declined by 6% and 42%, respectively. When moist curing was used, the 28 days compressive strength was declined by 13% and 71% with including 10% and 80% PG, respectively, whilst the flexural strength was declined by 15% and 90%, respectively, and the tensile strength was declined by 9% and 60%, respectively.

### 6.3 Concretes

Srinivasulu and Raghava (2017) depicted higher compressive strength of concretes with including 2.5%, 5% and 7.5% PG as cement substitution, whilst further substituted levels (7.5% and 10%) decreased it. Buhari and Raju (2016) depicted 4.11% enhancement in the 7 days flexural strength of concretes with including 5% PG as cement substitution, whilst including 7.5%, 10%, 12.5% and 15% PG caused a declination of 5.5%, 10.95%, 28.1% and 30.82%, respectively. The 28 days flexural strength was enhanced by 5%, 10%, 13% and 3% with including 5%, 7.5%, 10% and 12.5%, respectively, whilst including 15% PG caused 2.73% declination. Bhaduria et al. (2006) depicted 6.45%, 12.2% and 7.25% enhancement in the 28, 35 and 45 days compressive strength of concretes with including 5% PG as cement substitution, respectively, whilst including 10% PG declined it by 24.59%, 10.8% and 20.2%, respectively. The introduction of 15% PG declined the 28, 35 and 45 days compressive strength by 35.1%, 24.8% and 30.6%, respectively, whilst including 20% PG declined it by 47.58%, 32.37% and 40.38%, respectively. Umadevi et al. (2016) depicted 8.5% enhancement in the compressive strength of concretes containing 0.75% steel fibers with including 10% PG as cement substitution, whilst including 20% and 30% PG caused 30.9% and 47.3% declination, respectively. Similar tendency **of the results** was observed for splitting tensile strength. Sindhuja et al. (2016) depicted 7% enhancement in the compressive strength of concretes with including 10% PG as cement substitution, whilst including 20% and 30% caused 31.35% and 46.86% declination.

Deepak et al. (2016) depicted a declination in the compressive strength of concretes with including PG as cement substitution. The introduction of 10%, 20% and 30% PG caused 1.1%, 37.84% and 44.32% declination in the 7 days compressive strength, respectively, whilst the 28 days compressive strength was declined by 1.25%, 38.28% and 44.44%, respectively.

Alam et al. (2015) depicted 2.23%, 19.38%, 34.1% and 56.35% declination in the 28 days compressive strength of concretes with including 10%, 20%, 30% and 40% PG as cement

substitution, respectively, whilst the tensile strength was declined by 0.64%, 18.1%, 30% and 51.61%, respectively. Reddy et al. (2010) partially replaced cement in concretes with PG at levels of 10%, 20%, 30% and 40%. Different w/b ratios ranging from 0.4 to 0.65 were used. The results depicted 1% enhancement in the 28 days compressive strength with including 10% PG, whilst including 20%, 30% and 40% PG caused a declination of 10.45%, 36.1% and 66.2%, respectively, when w/b ratio was 0.4. At w/b ratio of 0.65, the introduction of 10% PG enhanced the 28 days compressive strength by 2.1%, whilst including 20%, 30% and 40% PG declined it by 25.48%, 44.37% and 71.11%, respectively. Similar tendency of the results was observed for splitting tensile strength. They concluded that cement can be replaced with 10% PG to achieve good strength, whilst replacing cement with higher levels than 10% PG led to a drastic strength declination.

#### 6.4 Bricks

Godinho-Castro et al. (2012) reported that ceramic blocks can be manufactured from 35% non-plastic clay, 35% plastic clay, 20% gypsum waste and 10% cement. Compressive strength of 4.64 MPa can be obtained. Garg et al. (2011) manufactured masonry from chalk (45%), cement (50%) and PG (5%). Compressive strength of 5.2 and 12.1 MPa can be obtained at ages of 7 and 28 days, respectively. Kumar (2000) reported that calcined PG in proportions of 20-40% can be used with FA-lime binders to produce bricks with suitable compressive strength. Kumar (2002) manufactured bricks from 60% FA, 30% lime and 10% calcined PG, then lime was partially replaced with 10% and 20% calcined PG. The results depicted higher compressive strength with increasing calcined PG content. Naik et al. (2014) manufactured bricks from 25% PG, 25% FA and 50% cement, then cement was

partially replaced with 5% PG coupled with 5% FA, 10% PG coupled 10% FA, 15% PG coupled 15% FA and 20% PG coupled with 20% FA. The results depicted a declination in the 7, 14 and 28 days compressive strength with including PG coupled with FA. This declination was increased with **increasing** cement replacement levels. The declination in the 28 days compressive strength was 12.27%, 22.52%, 25.9% and 49% with including 30% PG coupled with 30% FA, 35% PG coupled **with** 35% FA, 40% PG coupled **with** 40% FA and 45% PG coupled with 45% FA, respectively. [Yang et al. \(2009\)](#) autoclaved PG at steam pressure of 0.12 MPa with 120 °C for 16 h. The autoclaved PG was mixed with FA, lime and sand to **manufacture** bricks. The proportions of PG were 30%, 40% and 50%. The results depicted a declination in the compressive strength and flexural strength with **increasing** PG content. The declination in the compressive strength with including 40% and 50% PG was about 33.33% and 54.17%, respectively, compared to those containing 30% PG. [Zhou et al. \(2014\)](#) manufactured non –fired bricks from PG, lime and sand. The percentage of PG, lime and sand fluctuated from 65% to 85%, 1.33% to 1.73% and 22.67% to 13.27%, respectively. Low pressure of 10 MPa was used in press-forming. The results depicted higher compressive strength with **increasing** PG content up to 75%, whilst including PG at levels higher than 85% caused a declination in the compressive strength.

[Türket and Aksin \(2012\)](#) manufactured bricks from clay, then clay was partially replaced with PG at levels ranging from 5% to 30%. The results depicted lower flexural strength with including PG. The introduction of 5%, 10%, 15%, 20%, 25% and 30% PG caused 18.18%, 22.73%, 31.82%, 29.54%, 18.18% and 18.18% declination in the flexural strength, respectively. The introduction of 10% PG enhanced the compressive strength by 1.11%, whilst the introduction of 5%, 15%,

20%, 25% and 30% PG declined it by 10.86%, 26.18%, 17%, 6.41% and 3.34%, respectively. Ajam et al. (2009) manufactured clay bricks from 70% clay and 30% sand, then clay was partially replaced with PG (size 50  $\mu\text{m}$ ) at levels ranging from 5% to 40%. The results depicted 28.9%, 27.87%, 36.83%, 41.26% and 61% declination in the compressive strength with including 5%, 15%, 25%, 30% and 40% PG, respectively.

The recorded studies in Section 6, in general, show that the introduction of untreated PG in the matrix declined its strength (Fig. 3). This declination was increased with increasing PG content. The impurities in PG are the main reasons for strength degradation especially at early ages. On the other hand, in most cases, the introduction of treated or calcined PG, up to a certain level, in the matrix enhanced its strength or at least mitigated the strength degradation caused by untreated one (Fig. 4). The purified PG shorted the setting time and the strength was augmented due to the removal of  $\text{P}_2\text{O}_5$ ,  $\text{F}^-$ , organic matter and alkalis impurities during treatment/calcination (Singh, 2002).

## 7. Water absorption and permeability

Kumar (2002) manufactured bricks from 60% FA, 30% lime and 10% calcined PG, then lime was partially replaced with 10% and 20% calcined PG. The results depicted a declination in the water absorption with increasing calcined PG content. The declination in the water absorption was 10.7% and 14% with including 20% and 30% calcined PG, respectively, compared to those containing 10% calcined PG. Sindhuja et al. (2016) depicted a declination in the chloride ion permeability of concretes with including 10%, 20% and 30% PG as cement substitution. The introduction of 30% PG caused 21.13% and 18.84% declination in the chloride ion

permeability at ages of 28 and 90 days, respectively. Huang et al. (2016) prepared concrete mixture from 45% pretreated PG (surface area 281.9 m<sup>2</sup>/kg), 49% slag, 2% steel slag, 4% clinker as well as aggregates. The results showed a significant declination in the chloride diffusion coefficient (chloride permeability) of PG concrete in comparison with Portland cement concrete. This declination reached about 73.35%. The declination in the chloride permeability could be relevant to more formation of low Ca/Si C-S-H gel due to the activation of slag with PG and clinker. Bouchhima et al. (2013) manufactured bricks from 60% PG (size 250 µm), 32% natural sand, 5% cement and natural hydraulic lime, then natural sand was partially replaced with 10% and 20% PG. The results depicted lower water absorption with including PG as natural sand replacement. The introduction of 70% and 80% PG in the bricks led to 5.12% and 10% declination in the water absorption in comparison with those containing 60% PG.

Taher (2007) depicted that slag cement containing 6% PG (size < 90 µm) exhibited higher total porosity than those containing 6% raw gypsum, whilst using PG after calcination at 200, 400, 600 and 800 °C for 2 h decreased the total porosity. The total porosity was decreased with increasing calcination temperature. Türket and Aksin (2012) manufactured bricks from clay, then clay was partially replaced with PG at levels ranging from 5% to 30%. The results depicted 10%, 15% and 5% increment in the water absorption with including 5%, 15% and 20% PG, respectively, whilst including 10% and 30% PG declined it by 5%. Ajam et al. (2009) manufactured clay bricks from 70% clay and 30% sand, then clay was partially replaced with PG (size 50 µm) at levels ranging from 5% to 40%. The results depicted that the introduction of 5% and 15% PG declined the water absorption coefficient of the bricks by 25.87% and 20.28%, respectively, whilst the introduction of 25%, 30% and 40% PG increased

it by 7%, 56.64% and 87.41%, respectively. Naik et al. (2014) manufactured bricks from 25% PG, 25% FA and 50% cement, then cement was partially replaced with 5% PG coupled with 5% FA, 10% PG coupled with 10% FA, 15% PG coupled with 15% FA and 20% PG coupled with 20% FA. The results depicted 3.69% increment in the water absorption with including 30% PG coupled with 30% FA, whilst including 35% PG coupled with 35% FA, 40% PG coupled with 40% FA and 45% PG coupled with 45% FA caused a declination of 14.95%, 30.86% and 3.65%, respectively.

Değirmenci (2008) manufactured binder mixture from FA (90%) and hydrated lime (10%), then FA was partially replaced with PG (fineness 467 m<sup>2</sup>/kg) at levels ranging from 10% to 50%. The results depicted an increment in the water absorption with including PG. The introduction of 10% and 50% PG increased the water absorption by 7.14% and 42.86%, respectively. Similar tendency of the results was reported by (Değirmenci and Okucu, 2007). They also used PG after calcination at 150 °C for 2 h. The results depicted 20% and 130% increment in the water absorption with including 10% and 50% calcined PG, respectively. Singh and Garg (1995) prepared mixtures from calcined PG (fineness 350 m<sup>2</sup>/kg) and slag with the ratios of 70:24, 65:30, 60:35 and 50:50. Ca(OH)<sub>2</sub> (2-3%), Na<sub>2</sub>SO<sub>4</sub>.10H<sub>2</sub>O (1.5-2%) and FeSO<sub>4</sub>.7H<sub>2</sub>O (1-1.5%) were incorporated in these mixtures. The results depicted higher water absorption with increasing calcined PG content. Compared to the mixture containing 50% calcined PG, the water absorption was increased by 4.82%, 9.95% and 13.51% with including 60%, 65% and 70% calcined PG, respectively.

The recorded studies in this section reveal that there are contradictor results about the effect of PG on the water absorption and permeability of the matrix (Fig. 5), but in general the introduction of treated/calcined PG exhibited lower water absorption and permeability than those including untreated one. Whatever, it is

completely known that as the compressive strength of the matrix declined, the density also declined, but the water absorption and permeability increased. Thus, the water absorption and permeability depend on the compressive strength and density of the matrix.

## 8. Chemical resistance

[Mun and So \(2008\)](#) partially replaced cement in mortars with 7.5% calcined PG. The specimens were steam cured at 65 °C for 6 h. After 14 days, the specimens were exposed to 5% and 10% sulfuric acid ( $H_2SO_4$ ) and 5% hydrochloric acid (HCl) for 14, 28 and 56 days. The results depicted lower weight loss of specimens containing calcined PG compared to the control. This means higher acid resistance of mortars with including calcined PG. [Kumar \(2002\)](#) manufactured bricks from 60% FA, 30% lime and 10% calcined PG, then lime was partially replaced with 10% and 20% calcined PG. Bricks were cured in  $Na_2SO_4$  solution. The results depicted higher sulfate resistance with **increasing** calcined PG **content**. After curing in sulfate solution, the reduction in the compressive strength was 13.6%, 13.5% and 9.2% with including 10%, 20% and 30% calcined PG, respectively. [Naik et al. \(2014\)](#) depicted lower degradation in the bricks compressive strength cured in sulfate solution with **increasing** PG content from 25% to 30%, 35%, 40% and 45%.

The recorded studies in this section confirm that the influence of PG on the chemical resistance of the matrix still requires more investigations to obtain general conclusions. Whatever, according to the available three studies, the introduction of calcined PG in the matrix increased its resistance against HCl and  $Na_2SO_4$ . This could be relevant to the denser microstructural which **the** ettringite caused ([Mun and So, 2008](#)).

## 9. Shrinkage and expansion

[Yang et al. \(2016\)](#) prepared self-leveling mortar mixture containing 20% cement, 40% PG and 40% natural sand. The natural sand was partially replaced with 5%, 10% and 15% PG. (size 1.6-208.9  $\mu\text{m}$ ). The results showed higher shrinkage with including PG. The shrinkage was increased by 300% with **increasing** PG content from 40% to 55%. [Ajam et al. \(2009\)](#) manufactured clay bricks from 70% clay and 30% sand, then clay was partially replaced with PG (size 50  $\mu\text{m}$ ) at levels ranging from 5% to 40%. The results depicted 0.6%, 8.11%, 0.6%, 12.61% and 50.15% increment in the shrinkage coefficient of the bricks with including 5%, 15%, 25%, 30% and 40% PG, respectively. [Türket and Aksin \(2012\)](#) manufactured bricks from clay, then clay was partially replaced with PG at levels ranging from 5% to 30%. The results depicted 7.3%, 11.6%, 9.52%, 21.43% and 16.67% increment in the drying shrinkage with including 10%, 15%, 20%, 25% and 30% PG, respectively, whilst including 5% PG declined it by 11.11%. On the other hand, the total shrinkage was declined by 50.58%, 41.17%, 39.1%, 37.2%, 27.5% and 25.42% with including 5%, 10%, 15%, 20%, 25% and 30%, respectively

[Bhaduria et al. \(2006\)](#) and [Bagade and Satone \(2012\)](#) partially replaced cement in pastes with 5%, 10%, 15% and 20% PG. The results depicted higher soundness expansion with including PG. The soundness expansion was increased by 100%, 200%, 400% and 700% with including 5%, 10%, 15% and 20% PG, respectively. In such a way, [Bhaduria et al. \(2006\)](#) depicted 100%, 200%, 400% and 700% increment in the soundness expansion of cement mixtures with partially replacing cement with 5%, 10%, 15% and 20% and 25% PG, respectively. [Smadi et al. \(1999\)](#) found higher soundness of cement paste mixtures with including PG. The

introduction of 10%, 20%, 30%, 40%, 50%, 60% and 70% PG led to 20%, 47.5%, 75%, 100%, 107.5%, 125% and 150% increment in the soundness expansion, respectively. Singh and Garg (1995) prepared mixtures from calcined PG (fineness 350 m<sup>2</sup>/kg) and slag with the ratios of 70:24, 65:30, 60:35 and 50:50. Ca(OH)<sub>2</sub> (2-3%), Na<sub>2</sub>SO<sub>4</sub>.10H<sub>2</sub>O (1.5-2%) and FeSO<sub>4</sub>.7H<sub>2</sub>O (1-1.5%) were added to these mixtures. The results depicted higher soundness expansion with increasing calcined PG content. Compared to the mixture containing 50% calcined PG, the soundness expansion was increased by 8.57%, 14.3% and 15.71% with including 60%, 65% and 70% calcined PG, respectively. Huang and Lin (2010) depicted higher 3, 7 and 28 days expansion of specimens manufactured from PG-steel slag-slag-limestone with increasing PG (fineness 813 m<sup>2</sup>/kg) content from 25% to 35%, 45%, 55% and 65%.

The recorded studies in this section confirm that the influence of PG on the shrinkage of the matrix still requires more investigations to obtain reasonable general conclusions. Whatever, according to the available few studies, the introduction of PG in the matrix increased its shrinkage. In such a way, the incorporation of PG in the matrix increased its soundness expansion. This increment in the expansion could be relevant to the formation of more ettringite (Smadi et al., 1999). Increasing drying shrinkage and soundness expansion with including PG are two major defects which limit its wide use.

## **10. Other durability properties and thermal conductivity**

Yang et al. (2016) prepared self-leveling mortar mixture containing 20% cement, 40% PG and 40% natural sand. The natural sand was partially replaced with 5%, 10% and 15% with PG. (size 1.6-208.9 μm). The results showed lower abrasion resistance with including PG. The wear loss was increased by 40.74% with increasing

PG content from 40% to 55%. Yang et al. (2009) reported good freeze-thaw resistance of bricks manufactured from 40% autoclaved PG (at steam pressure of 0.12 MPa at 120 °C for 16 h), 15% FA, 15% lime, 29% natural sand and 1% additive. After 15 cycles at temperature of -20 °C to 20 °C, the **declination** in the weight loss was only 0.029%, whilst the **declination** in the compressive strength was 21%. Umadevi et al. (2016) depicted higher fire resistance of concretes containing 0.75% steel fibers with including 10% PG as cement substitution after exposure to 100, 200 and 300 °C for 4, 6 and 8 h, whilst including 20% and 30% PG caused a declination in the fire resistance. Similar tendency **of the results was obtained for** splitting tensile strength. Değirmenci and Okucu (2007) prepared binder mixture from FA (90%) and hydrated lime (10%), then FA was partially replaced with PG (fineness 467 m<sup>2</sup>/kg) at levels ranging from 10% to 50%. The results depicted higher thermal conductivity with including PG. The thermal conductivity of the different mixtures was between 0.360-0.378 W/mK.

The recorded few studies in this section confirm that the influence of PG on the abrasion resistance, freeze-thaw resistance, fire resistance and thermal conductivity of the matrix still requires more investigations to obtain general conclusions. Whatever, the introduction of PG in the matrix declined its abrasion resistance. It is logical result because the abrasion resistance of the matrix is closely related to its compressive strength. On the other hand, the introduction of PG in the matrix increased its freeze-thaw resistance. In such a way, including 10% PG in the matrix increased its fire resistance, **whilst** higher levels than 10% declined it. The introduction of PG has negative effect on thermal conductivity.

## 11. Modification strategies

### 11.1 Curing conditions

Kumar (2002) depicted higher compressive strength of bricks manufactured from 20% calcined PG, 60% FA and 20% lime cured at 50 °C in comparison with those cured at ambient temperature. Belz et al. (1994) depicted that cementitious specimens manufactured from calcined PG, FA, slag, cement and/or hydrated lime cured at 70 °C or 85 °C exhibited higher compressive strength than those cured at 55 °C. Min et al. (2008) stated that curing binders manufactured from FA, lime and calcined PG at 45 °C with 90% RH increased the compressive strength in comparison with those cured at room temperature. The 1, 3, 7, 28 and 90 days compressive strength of specimens containing 8% calcined PG, 70% FA and 30% lime cured at 45 °C with 90% RH was enhanced by 49.75%, 29.22%, 41.35%, 21.86% and 4.48% over those cured at room temperature, respectively.

Singh and Garg (1995) manufactured mixture from 40% calcined PG (surface area 300 m<sup>2</sup>/kg), 40% FA and 20% hydrated lime. They stated that the compressive strength can be enhanced by increasing curing temperature from 27 °C to 40 °C and 50 °C. Curing specimens at 50 °C led to 5.5%, 53.53%, 283.58%, 575.76% and 165.1% enhancement in the 1, 3, 7, 28 and 90 days compressive strength in comparison with those cured at 27 °C. Similar tendency of the results was obtained by (Garg et al., 1996). In such a way, Singh and Garg (1997) modified the compressive strength of cementitious specimens manufactured from 40% calcined PG (fineness 320 m<sup>2</sup>/kg), 40% FA, 10% lime and 10% cement by increasing curing temperature from 27 °C to 40 °C and 50 °C. The results depicted that curing specimens at 40 °C and 50 °C increased the 3 days compressive strength by 1.5 to 2 times greater than those cured at 27 °C, whilst the 7, 28 and 90 days compressive strength was enhanced by 2 to 2.5 times greater. Yang et al. (2009) exposed PG to two different types of

autoclave conditions (low or high). In the low autoclave condition, the PG was exposed to steam pressure of 0.12 MPa at 120 °C for 16 h, whilst in the high one the PG was exposed to steam pressure of 0.8 MPa at 180 °C for 8 h. Each PG type was mixed with FA, lime and sand to manufacture bricks. The results depicted higher compressive strength and flexural strength with using autoclaved PG. The compressive strength was enhanced by about 96% and 15% by using low and high autoclaved PG, respectively.

The recorded studies in this section reveal that increasing curing temperature of PG matrix from room temperature to 45, 50, 55, 70 and 85 °C led to an enhancement in the compressive strength especially at early ages. Curing at temperatures higher than room temperature accelerate the hydration, and increase the intensity of the endotherms of ettringite and tobermorite as well as decrease the intensity of the endotherms of gypsum and lime (Singh and Garg, 1995).

## 11.2 Fibers

Hua et al. (2016) prepared mixture containing 60% PG (surface area 350 m<sup>2</sup>/kg), 40% slag and 4% lime modified with different fiber types (mineral, glass and polypropene). Different mineral and glass fibers contents fluctuated from 0.35% to 1%, by volume, were incorporated, whilst the contents of polypropene fibers fluctuated from 1% to 1.7%. The results showed higher flexural strength, freeze/thaw resistance, anti-impact work and water resistance with the introduction of fibers. The polypropene fibers showed the optimum type, whilst 1.35% showed the optimum content. The 28 days flexural strength was enhanced by 48.81%, 51.19% and 44% with including 1%, 1.35% and 1.7% polypropene fibers, respectively, whilst the impact work was enhanced by 191.33%, 388% and 299.5%, respectively. After 15

cycles of freezing in air at  $-20 \pm 2$  °C for 2 h and thawing in water at  $20 \pm 2$  °C for 3 h, the declination in the weight loss was 13.2%, 1.9%, 1.7% and 1.6% with including 0%, 1%, 1.35% and 1.7% polypropene fibers, respectively.

The recorded study in this section confirms that using fibers to modify some properties of PG matrix still requires more investigations. Whatever, adding 0.35-1% mineral or glass fibers or 1-1.7% polypropene fibers can improve flexural strength, freeze/thaw resistance, anti-impact work and water resistance. This improvement was increased with increasing fibers content.

### 11.3 Superplasticizer and NaOH

Garg et al. (2016) tried to modify some properties of calcined PG plaster by adding naphthalene formaldehyde condensate superplasticizer (SP) (0.1-1.2%) and polycarboxylate SP (0.1-1.2%) separately. The results depicted that as the content of SP increased the compressive strength increased, whilst the water absorption declined. The incorporation of 0.6% naphthalene formaldehyde condensate SP and polycarboxylate SP contributed 75% and 71.5% enhancement in the compressive strength, respectively. Huang and Lin (2010) tried to modify some properties of mixture manufactured from PG (fineness 521 m<sup>2</sup>/kg) (45%), slag (40%), limestone (10%) and steel slag (5%) by adding 1-3% NaOH. The results depicted that the higher the NaOH amount the shorter the setting time was obtained. The 3 and 7 days compressive strength and flexural strength was enhanced with including NaOH, whilst the 28 days strength did not affect by 1% NaOH and was decreased significantly by adding 2% or 3% NaOH. The enhancement in the 3 days compressive strength with adding 1%, 2% and 3% NaOH was 74.51%, 111.76% and 92.16%, respectively, whilst the enhancement in the 7 days compressive strength was 92.45%,

47.2% and 13.21%, respectively. The enhancement in the 3 days flexural strength was 121.43%, 85.71% and 92.86%, respectively, whilst the enhancement in the 7 days flexural strength was 38.71%, 32.26% and 29%, respectively.

The recorded studies in this section **confirm** that using SP or NaOH to modify some properties of PG matrix still requires more investigations. Whatever, according to the available two **studies**, adding 0.1-1.2% SP can enhance the compressive strength and decline the water absorption, whilst adding 1% NaOH can enhance the mechanical strength and **decline** setting time,

## 12. Advantages, shortages and applications

The introduction of PG in the matrix depicted some advantages, while some **properties** are improved and some shortages, while some **properties** are deteriorated (**Table 2**). The advantages of including PG in the matrix are reducing density, increasing chemical resistance, increasing freeze/thaw resistance and increasing fire resistance (for 10% PG). On the other hand, the shortages of **including** PG in the matrix are decreasing workability, decreasing mechanical strength, decreasing abrasion resistance, increasing drying shrinkage, increasing soundness expansion and increasing thermal conductivity. Increasing setting time can be considered as an advantage or a shortage according to the application of PG which used for. Whatever, some of the mentioned disadvantages of using PG can be alleviated by **applying** different additives/methods as reported in the previous section. It is noteworthy mentioning that regardless the negative effect of PG on some properties, reusing PG in building materials has **a** major positive effect on mitigating the contaminations which **the disposal of PG** caused.

PG can be used extensively in cement, wallboard, ferrocement panels, plasterboard panels, partition blocks, plaster, tiles, artificial stone, glass ceramics and other building materials. PG mixed with FA, aggregate or cement can be used as a base for roads, storage areas and parking lots. PG can be used in sulfur polymer concrete (García-Díaz et al., 2016), polymer flooring composition (Singh and Garg, 2005) and polymer composites (Vebeek and du Plessis, 2005; López et al., 2011). Recently, PG can be used to enhance the compressive strength of FA-based geopolymers before and after exposure to elevated temperature, of which Rashad (2015) found higher compressive strength of FA-based geopolymer pastes activated with sodium silicate by partially replacing FA with 5% and 10% calcined PG. In addition, specimens containing 5% and 10% PG depicted higher fire resistance than the control after being exposed to temperatures ranging from 200 to 1000 °C for 2 h.

### 13. Remarks

1. PG can be **purified** by different methods such as washing with tap water, milk of lime, sulphuric acid, calcination and a calcination after suitable treatment with sulphuric acid.
2. Including PG in the matrix reduced the workability, unit weight and mechanical strength due to its low density.
3. Including treated/calcined PG in the matrix up to a specific level could improve the mechanical strength or at least mitigate the strength degradation.
4. The influence of PG on the chemical resistance of the matrix still lack and requires more investigations to get general conclusions. Whatever, according to the available few studies, including calcined PG enhanced hydrochloric acid

and sulfate resistance. This could be relevant to the denser microstructural which ettringite caused.

5. Including PG in the matrix has negative effect on drying shrinkage as well as soundness expansion. These two defects limit the wide use of PG.
6. The influence of PG on the abrasion resistance, freeze/thaw resistance, fire resistance and thermal conductivity still requires more investigations. Whatever, according to the available few studies, including PG in the matrix decreased the abrasion resistance, but increased the freeze-thaw resistance. Including 10% calcined PG increased fire resistance, whilst higher amounts decreased it.
7. Some properties **of the** matrix containing PG could be modified by applying suitable curing conditions, adding 0.35-1% mineral or glass fibers, 1-1.7% polypropene fibers, 0.1-1.2% SP or adding 1% NaOH.

According to this review, there are a lot of studies regarding to recycling of PG as a part of building materials, but most of these studies concentrated on mechanical strength (30.56%), setting time (13.89%), purification (18.52, water absorption and permeability (10.19%), workability (6.48%), unit weight (5.56%) and expansion (5.56%), whilst less attention was focused on chemical resistance (2.78%), drying shrinkage (2.78%), abrasion resistance (0.93%), freeze thaw resistance (0.93%) and thermal conductivity (0.93%) ([Fig. 6](#)). Adversely, there are shortages in studying **other properties** such as the effect of PG on alkali silica reaction, carbonation resistance and corrosion resistance. In addition, there are missed information about the **costs** of using different purification methods **required to purify PG** compared to those without purification. Furthermore, there is only one study which employed calcined PG in FA-based geopolymers. The

incorporation of PG in geopolymmer systems needs more and more studies. Thus, these points can be used for future works.

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Table 1 Oxide composition of PG for different studies

Constituent (%)	Değirmenci and Okucu (2007)	Min et al. (2008)	Ajam et al. (2009)	Huang and Li (2010)	Gaidučis et al. (2011)	Shen et al. (2012)	Bouchima et al. (2013)	Kadirova et al. (2014)	Rashad (2015)	Zhao et al. (2015)	Hua et al. (2016)	Huang et al. (2016)	Li et al. (2017)
SiO <sub>2</sub>	0.44	1.25	1.37	3.21	4.35	3.62	1.37	1.89	8.82	5.94	4.86	2.3	1.37
Al <sub>2</sub> O <sub>3</sub>	0.88	0.43	0.11	1.09	0.24	0.08	0.11	0.08	0.29	0.5	4.38	0.35	0.35
Fe <sub>2</sub> O <sub>3</sub>	0.32	0.21	0.03	0.31	0.06	0.05	0.03	-	0.35	1.54	-	0.27	0.45
CaO	32.04	29.05	32.8	34.52	34.35	31.57	32.8	36.48	32.14	32.12	31.05	31.64	38.39
MgO	-	-	0.007	0.06	0.72	0.17	0.007	-	0.09	0.3	0.26	0.29	0.12
SO <sub>3</sub>	44.67	42.19	44.4	47.3	51.11	42.48	44.4	49.89	34.51	46.02	30.95	42.1	56.68
P <sub>2</sub> O <sub>5</sub>	0.50	3.50	1.69	1.10	2.33	1.05	1.69	0.44	1.72	1.39	3.57	1.05	2.26
F <sup>-</sup>	0.79	-	0.55	0.20	0.5	-	0.55	-	0.8	0.06	-	0.2	-
Na <sub>2</sub> O	0.13	0.51	-	-	-	-	-	-	-	-	-	0.12	0.07
K <sub>2</sub> O	-	-	-	-	-	-	-	-	-	-	0.41	0.17	0.12
TiO <sub>2</sub>	-	-	-	-	-	0.06	-	-	-	-	0.2	-	0.06
LOI	21.06	19.48	22.3	11.01	6.34	19.88	22.3	11.22	21	-	-	21.19	-

Table 2 Advantages and shortages of using PG

Property	Positive effect	Negative effect
Unit weight	Yes	
Fire resistance (10% PG)	Yes	
Freeze/thaw resistance	Yes	
Sulfate resistance	Yes	
Sulfuric acid resistance	Yes	
Setting time	Yes	Yes
Workability		Yes
Mechanical strength		Yes
Abrasion resistance		Yes
Drying shrinkage		Yes
Soundness expansion		Yes
Thermal conductivity		Yes



Fig. 1 Raw PG

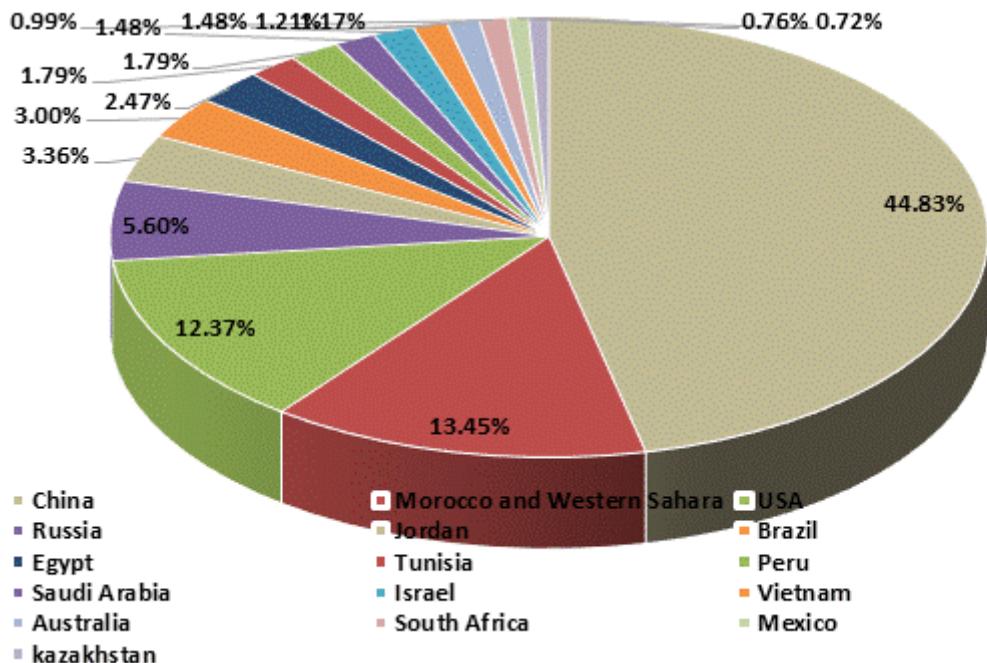


Fig. 2 The 15 top phosphate-producing countries

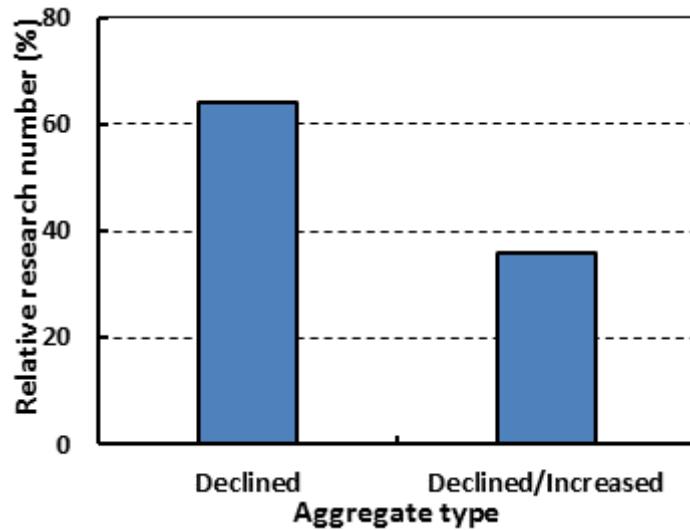


Fig. 3 Percentage of research number versus the effect of PG on mechanical strength of the matrix

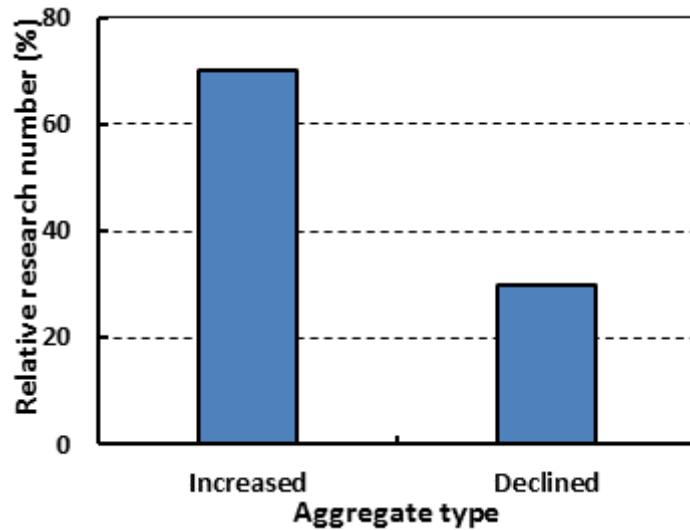


Fig. 4 Percentage of research number versus the effect of treated/calcined PG on mechanical strength of the matrix

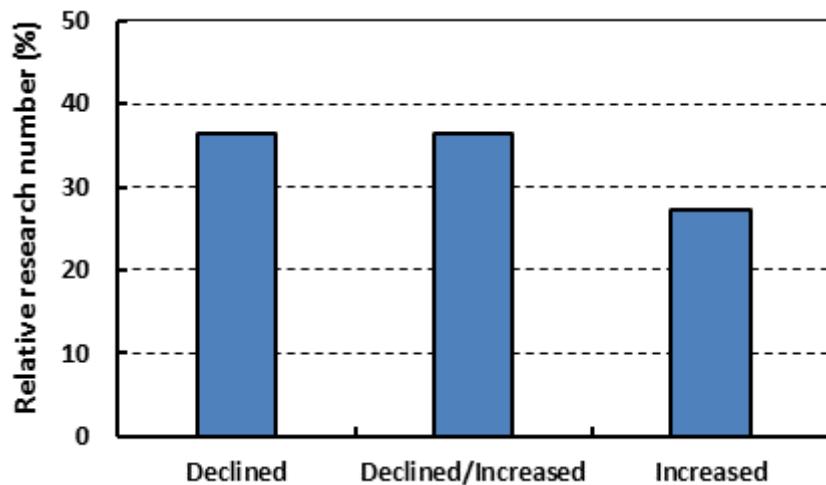


Fig. 5 Percentage of research number versus the effect of PG on water absorption and permeability of the matrix

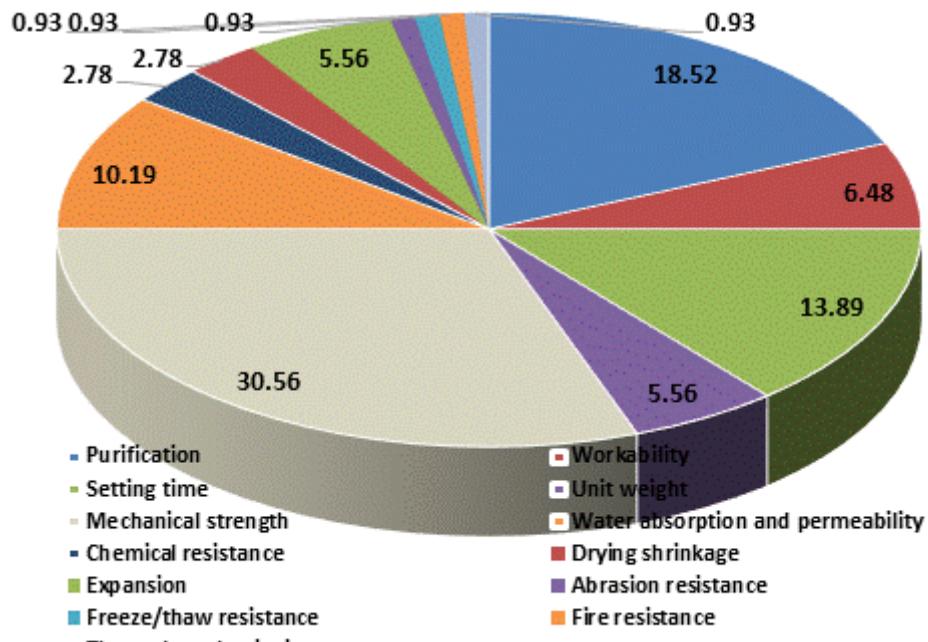


Fig. 6 Relative research number for the effect of PG on each property

**Highlights**

- Phosphogypsum (PG) is a by-product from the industry of phosphate fertilizer
- PG can be reused as a construction material
- Including PG in the matrix reduced its workability, density and mechanical strength
- Including PG in the matrix increased its shrinkage, expansion and water absorption
- There are different methods to modify some properties of PG matrix