Journal of the Thai Ceramic Society
Vol.1 [1], pp 30-42 (2025) Research article

Physical nature and water permeability of pervious concrete made from domestic electric arc furnace steel slag

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[Received : October 1, 2024 Revised : November 18, 2024 Accepted : December 19, 2024]

Abstract

A pervious material is a concrete-based perforated material that can effectively drain water according to its porous structure. The outstanding features of the structure include a large fraction of open and connected pores, allowing good water permeability. This research focused on the use of electric arc furnace (EAF) slag waste from the steel industry as a raw material to produce pervious concrete. This aimed to observe the relationship between properties and microstructure of the slag-based porous bodies, i.e. compressive strength, water permeability and porosity. The cast specimens were prepared as slag-cement mixtures containing 2 different median sizes of the crushed EAF slag, the particle sizes of which were 5-12 mm (M) and 12-20 mm (L). The mixtures with various EAF slag size, L:M ratio of 100:0, 75:25, 50:50, 25:75 and 0:100 by weight, were blended with ordinary Portland cement and water. After demolding and water curing for 1 day, the as-cast were further cured for 3, 7, 14 and 28 days. Compressive strength, density, porosity and water permeability were determined. The experimental results showed that the compressive strength was greater as a function of curing time. The change in EAF slag size ratio significantly affected the strength. Strength and water permeability were truly related to pore characteristics. The water flow rate might not be solely based on pore fraction in the bodies but also depended on the connectivity and the size of the pore. Therefore, the next step of the research should cover the connectivity of pore structure.

Keywords: Electric arc furnace (EAF) slag; Waste utilization; Pervious concrete; Porosity; Water permeability

Introduction

Pervious concrete is a perforated material that has porous patterns in its structure. These porous patterns provide a network of voids or openings with various sizes, shapes, configurations and levels of connectivity, depending on raw materials, manufacturing processes and intended purposes. There are several types of perforated materials, i.e. previous concrete, porous asphalt and interlocking pavers, depending on raw materials and processes. Mechanical properties, physical natures and their functions according to such highly porous structures are the state-of-art and are to be carefully compromised. According to the concrete-based type, the pervious concretes typically have stable porous structures with interconnected voids of 15-25%, offering compressive strength of 2.8-28 MPa and water percolation rate of 0.14-1.22 cm/sec [1]. The key function of the pervious concretes in pavement and road applications is to allow water to pass through the connected porous structure to the well-organized bedding layers or water draining system lying beneath in order to minimize the risk of flooding. These materials can also perform sound absorption and improve air flow that can reduce road temperature.

In the pavement and road aspects, previous concretes and porous asphalts are most commonly used. They both contain similar skeleton materials, i.e. coarse aggregates, to create porous fashion but differ in binding materials, either cement or asphalt, respectively. Aggregate materials including rocks, gravels, crushed stones and steel slags. Steel slags are by-products from recycling and can be categorized by melting or refining processes they are produced [2], such as blast furnace, basic oxygen furnace, electric arc furnace and ladle furnace. Steel slags generally comprise various oxide contents, e.g. CaO, SiO_2, Al_2O_3, MnO, MgO, Fe_2O_3 and P_2O_5, [3-6, 9, 11] accompanying with more or less metal steel bead as an inclusion. Normally, the mixture may or may not include a small amount of fine aggregates due to the fact that these aggregates can promote compaction, which attribute negative effects to the pervious characteristics. As far as steel slags are concerned, not every steel slag is suitable to employ as perforated raw materials. Blast furnace (BF) slag is always a partial replacement material for cement or supplementary cementitious materials. Ladle furnace (LF) slag contains high levels of basicity due to high degree of free lime to silica ratio. The existence of undissolved free lime (CaO), free magnesia (MgO) and sulfide compounds can hydrate and generate delayed volume expansion when exposed to water. Electrical are furnace (EAF) slag, the main by-product of steel production, provides similar composition to earth crust and is relatively chemically stable, so EAF slag is the most commonly used slag in civil and road applications. The oxides presented can be several oxide phases, in the forms of mono oxides and complexed oxides [4-5], such as wustite (FeO), hematite (Fe_2O_3), larnite or beta-calciumsilicate (β-Ca_2SiO_4), merwinite ($Ca_3MgSi_2O_8$) and brownmillerite or calcium ferroaluminate ($Ca_2(Al,Fe)_2O_5$). Apart from environmental and economic points of views, the technical advantages of EAF slag over earth crusts include no organic impurities and stable chemical composition, which directly influence concrete durability. The density of EAF slag is higher than other natural aggregates, in the range of 2.8-3.9 g/cm^3, depending on EAF slag sources of origin [6-7]. Also, the EAF slag also offers low water absorption (mostly 0.5-4%), high hardness and friction coefficient, offering heavy-duty, load-bearing, abrasive and wear resistant services. According to the combination of these unique properties, the use of EAF slag has recently become more and more favorable, not ending at the landfill in vain [5, 7].

To employ as an aggregate material in the normal concrete, the crushed EAF slag benefits in the terms of interlocking and hardness. EAF slag is also compatible with other components in concrete mixtures it can achieve greater density and strength development compared to siliceous aggregates. Many research works have studied the use of EAF slag in asphalt and various concretes, e.g. hydraulic concrete and high performance concrete. A study conducted by Ćosić et al. [8] suggested that pore connectivity was influenced by the aggregate type than the size while the flexural strength depended on amount of smaller aggregates. By the use of dolomite-based and steel slag-based pervious concrete, the work noticed a profound interlocking and greater mechanical strength in the steel slag-based ones. Other works also revealed the reinforced concrete beams could reach their ultimate flexural strength and shear capacity when coarse recycled EAF slag was partially substituted to natural aggregates [4, 8-10, 12, 15-16]. A combination of coarse EAF slag aggregates and disposable construction/demolition waste in the fly ash-containing concrete mix suggested that coarse EAF slag could recover strength and durability relative to ones without EAF slag [6, 9-10]. Durability against a freeze-thaw activity, high temperature and high relative humidity of the EAF slag containing concrete was also reported [11]. Volumetric expansion caused by long-term aging reaction in hydraulic concrete using EAF slag was also reported in some literatures [5, 10-12]. Some of them also concerned higher water demand, surface texture, interparticle friction and particle compaction of EAF slag on workability of the cement mix.

Recently, more literatures have focused the use of EAF slag in cement-based concretes. Chang et al. [14] investigated the properties of the previous concrete made with EAF slag and alkali activated slag. The work reported the improved interlocking from physical nature of EAF slag of 2.4-4.8 mm in size promoted high compressive strength up to 35 MPa after 28 days and allowed water permeability of 0.49 cm/sec. The same researchers [15] also later found that the cement type could influence the compressive strength of the EAF slag-containing (from 4.8-9.6 mm in aggregate size) pervious concrete and suggested that prolonged air curing could reduce strength due to loss of reaction water. Nadiatul Adilah et al. [16] indicated that the higher amount of EAF slag replacement to granite could enhance compressive strength. Such useful information are backgrounds in order to develop domestic EAF slag-bearing perforated products. It can be noticed that most of the works mentioned previously always employ relatively fine EAF slag particles and prepared the mixture of EAF slag replacement to the traditional natural aggregates in dense concretes, not perforated ones.

In Thailand, the commonly used commercial crushed EAF slags come from steel scrap recycling industries. The commercial crushed slags can be divided by their sizes, i.e. slag dust or small (S), medium (M) and large (L), the sizes of which are in the range of 0-5 mm, 5-12 mm and 12-20 mm, respectively. This work aimed to observe the characteristic and properties of the pervious concrete using domestic EAF slag alone as coarse aggregate. To prepare the pervious materials from EAF slag, the small slag was neglected because it seemed to offer particle packing rather than pore channel formation. Two different sizes of EAF slag, M and L, were selected to be mixed and cast into porous cylindrical blocks. Compressive strength and water permeability were then examined. The relationship between aggregate size ratio, porosity, and strength and water permeability was to be discussed.

Methods

Sample Preparation

The specimens were prepared from a slag-cement mixture comprising 3 main raw materials: EAF slag, ordinary Portland cement (OPC) and water. The approximate chemical composition and the crushed grains of the derived EAF slag is expressed in Table 1 and Fig. 1., respectively. The crushed EAF slag (Siam Steel Mill Services Limited, Thailand) was derived from steel making process. The crushed EAF slag was sieved to get different sizes of 5-12 mm (3/8") and 12-20 mm (3/4"), denoted as medium (M) and large (L), respectively. The selected EAF slag with different L:M ratio covered 100:0, 75:25, 50:50, 25:75 and 0:100 by weight. OPC was mixed with tap water with the water to cement (W/C) ratio of 0.33 and thoroughly blended in a mortar mixer. It was noted that superplasticizer, slag dust and sand were not employed in the mix. The proportion of slag mix and dry OPC by weight was 3:1. Then, the cement mortar was added into the prepared EAF slag mix and blended in the mortar mixer for a few minutes. The slag-cement mix was cast into a series of 8 mm in diameter PVC cylindrical mold. It was noted that the surface of the as-cast was to keep its flatness by pressing with a ram just after casting, in order that the cylindrical block specimens could undergo mechanical testing. The cast were left overnight, after that they were demolded and water cured as per ASTM C39M-18 for 1 day and oven dried at 60 ^{o}C overnight to improve hydration and promote early strength, prior to further curing for 3, 7, 14 and 28 days. To cure at 60 ^{o}C can significantly develop early strength, quicker than normal practice, and offer hydration peaks higher than cured at room temperature. The pervious concrete preparation and specimens are shown in Fig. 2. which were then ready for testing and characterization.

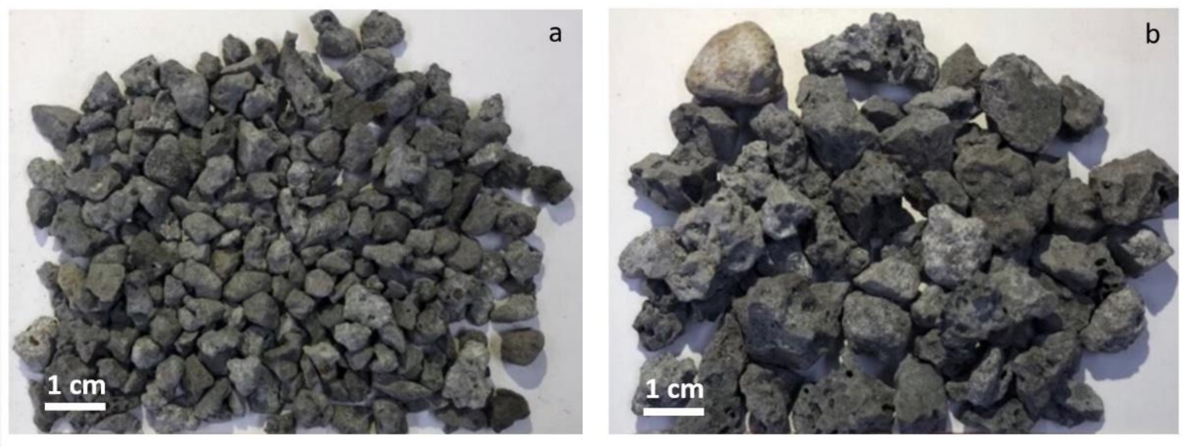


Fig. 1. Crushed EAF slag aggregates: (a) 5-12 mm and (b) 12-20 mm.

Table 1 Specification of chemical composition of the EAF slag (Siam Mill Services Limited, 2020).

Oxide composition	**Formula**	**Amount (wt%)**
Calcium oxide	CaO	25-30
Iron oxide	Fe_2O_3	20-25
Silicon oxide	SiO_2	10-20
Magnesium oxide	MgO	5-10
Manganese oxide	Mn_3O_4	5-6
Aluminum oxide	Al_2O_3	5-6

Fig. 2. The as-cast block specimens and the specimens during water curing.

Testing and Characterization

In this work, not only physical and mechanical properties the EAF slag-based pervious concretes were determined but the water permeability was also determined. Compressive strength of the specimens was carried out in accordance with ASTM C39 using a Universal testing machine (Industrial Series HDX model).

Density, porosity and water permeability were determined by a laboratory instrument setup based on Archimedes' principle. The actual density value included the exact weights of the dry porous structure presented in air (W_a), weights of the soaked structure (W_s) and the weight in water (W_w), as expressed in equation 1. It was noticed the weight of the dry specimen in air compared to those of the soaked was only slightly different according to high void content, the weight increase was as a result of water absorbed on the surface.

$$Actual\ density = \frac{W_a}{W_s - W_w} \qquad \text{Eq. 1}$$

Meanwhile, the theoretical density was calculated by the rule of mixture between EAF slag and cement fraction. Given the density values of raw materials, crushed EAF slag (measured by water immersion) of 3.30 g/cm^3, OPC of 3.20 g/cm^3 and water of 1.00 g/cm^3, the calculation was undergone regardless of hydration products. Due to the work varied the weight fraction of L and M slags with a fixed weight fraction of slag mix to dry OPC, their density values were therefore the same and led to the equivalent theoretical density of approximately 3.12 g/cm^3 in all batches. Percentage of void was measured and calculated from actual and theoretical density values as shown in equation 2

$$\%\ Calculated\ void\ content = \left(1 - \frac{actual\ density}{theoretical\ density}\right) \times 100 \qquad \text{Eq. 2}$$

It is not very straightforward to estimate the content of open porosity of the perforated ceramic bodies by water absorption like that of the dense ceramic bodies. In general, water retention of the ceramic bodies can reflect the content of open and connected pores when saturated with water, so called water absorption. For the pervious bodies which contain high fraction of interconnected pores and channels, however, water cannot be held and it runs out of the porous structure quickly once emerged from water. Instead, the degree of the void connectivity in the perforated body could be possibly implied from water retention. From pulp and paper characterization [17], the term retention is an empirical measure representing the capacity of a fiber test pad to hold water by fiber internal and external pores. Similar to fibers, the weight of water absorbed at the surface area of the interconnected pores relative to the dry is determined if the water immersion is undergone. Surprisingly, the calculation of water retention of pulp fiber is comparatively similar to water absorption in pervious bodies and possibly applied for the estimation, by the relative weight of water ($W_{wet} - W_{dry}$) of the soaked specimen to the dry one (W_{dry}). Thus the weight percentage of water absorbed over the porous surface are is expressed as equation 3:

$$\%\, Absorbed\, water = \left(\frac{W_{wet} - W_{dry}}{W_{dry}}\right) \times 100 \qquad \text{Eq. 3}$$

Finally, the water permeability was examined by the mean of constant head permeability test [18-19] in accordance with ASTM D2434. The testing apparatus is illustrated in Fig. 3., the water penetration with constant water pressure flowing through the perforated bodies was observed. Given Q is volume of water (cm^3), L is the length of the specimen (cm), H is the difference in height levels of the water inlet and outlet (cm), A is the cross-sectional area of the specimen (cm^2) and t is the flowing time (sec), therefore, the water permeability in cm/sec is calculated from expression in equation 4 as follows:

$$Water\, permeability = \frac{QL}{HAt} \qquad \text{Eq. 4}$$

It was noted that the volume of water, Q, was controlled as 2000 cm^3 and the height, H, was 13.4 cm according to our apparatus setup. Our experiment attempted to keep the dimension of the cylindrical blocks steady by controlling the weight of the slag-cement mix. They were between 18.30-19.60 cm in height (L) and 90-94 cm^2 in cross-sectional area (A), according to the PVC pipe mold.

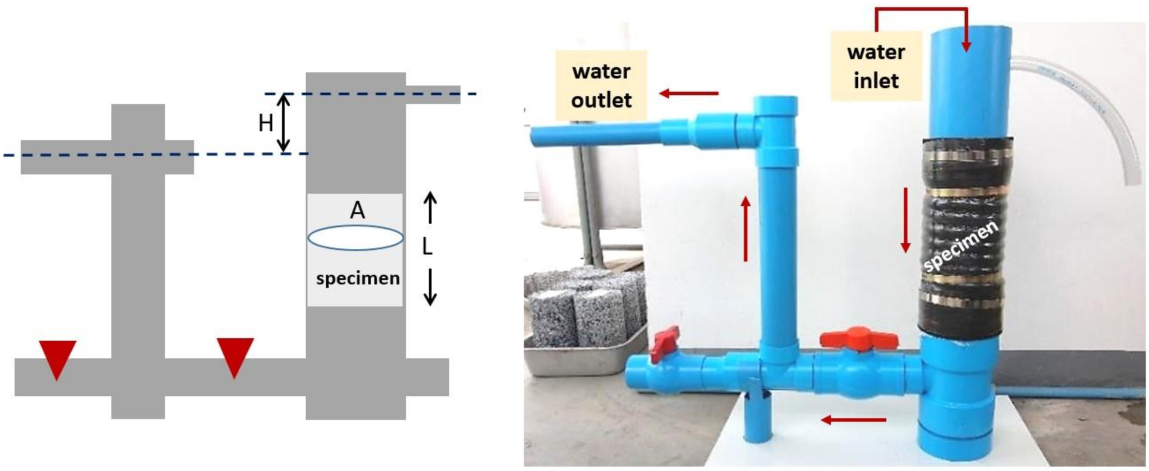


Fig. 3. Schematic and laboratory apparatus setup for water permeability.

Results and Discussion

Density and porosity

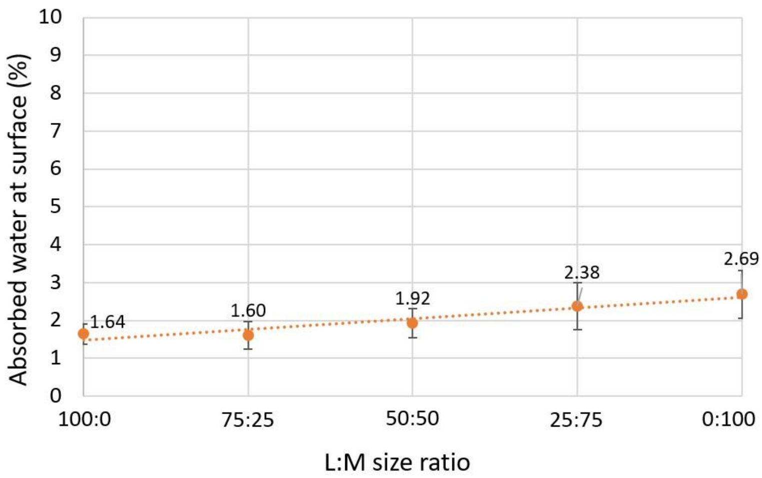
Density values of the porous specimens were measured by liquid immersion technique, water absorbed by open pore surface as well as porosity were calculated. The actual density values of the prepared specimens were between 2.38 -2.56 g/cm^3 while that of the calculated theoretical ones was 3.11 g/cm^3 due to the fixed composition of the slag-cement mix. When immerged in water, the specimens was likely to allow water to get in but could not hold most of water because of their relatively large open pores and voids, less than 3% absorbed by the pore surface. Physical nature of the EAF slag itself has very small water absorption [2, 4] and could be seen in the study. Fig. 4. (a) shows that a small amount of water attached to the porous structure surface. Meanwhile, Fig. 4. (b) suggests that the void content values of the specimens were in the range of 20-25% and the mixed L and M bodies had slightly lower void contents comparative to the monosized L and M. The aggregate packing can be observed from the fracture surface of the specimens as displayed in Fig. 5. From those illustrations, it was indicated that absorbed water was dependent on the aggregate size, packing and pore structure. In the single L bodies, the surface area might be lower than the single M bodies so the percentage of absorbed water was relatively low. As for the M-L bodies, they tended to absorb more water due to their various aggregate sizes. The other possibility was the connected pore channels in the M-L bodies (75:25, 50:50 and 25:75) and the single M (0:100) bodies might be narrow so that the water could be attached along these channels. However, according to Fig. 4. (b), the calculated void content in the monosized M was highest because the structures were likely to have close pores from irregular particles and the hydration products from cement binder could fill up the interparticle spaces, leaving isolated pores and voids. The similar void content in the porous structure could come from different levels of pore size and connectivity. It was noticed that higher surface water is most likely to imply higher surface area, which obtains from open and interconnected pore structure. However, surface area of the pervious structure might be not the only factor to be considered the natures and properties of pervious concrete. Other factors like packing, particle size and particle size distribution including pore size and distribution should have been observed and taken into account [8]. Unfortunately, the investigation of the pore connectivity of these specimens could not be achieved by CT scan or X-ray microtomography due to the limitation on the specimen size and inclusion embedded within. The attached steel beads from the steel recycling in EAF could be generally found in slags and such beads could make the artifact, resulting in smeared, unsatisfactory and misinterpreted images.

Compressive strength

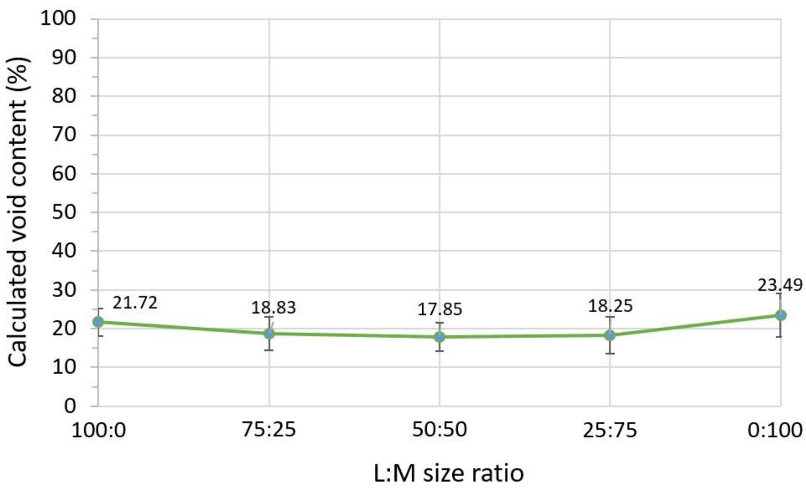
Compressive strength of the pervious concretes depended on size of the EAF slag aggregates, curing times and curing environment. According to our preliminary study [20], the comparison in strength study in the monosized S specimens being water cured and damped air cured (covered by wet cloth and kept in the lidded container) at 3 and 7 days was observed. The development in early strength in the 3-day cured specimens in water were about three times after greater than that cured in damped air. Similar trend could be seen in 7-day cured specimens in water, strength was higher than ones with damped air curing. This finding agreed with the work conducted by Ćosić et al [8] as well as Yeih and Chang [15]. The experimental results as expressed in Fig. 6. (a) showed the greater compressive strength development was found in the specimen with higher content M size at the same curing time. This was caused by the difference in aggregate packing, i.e., the finer aggregates, the denser bodies, and the interlocking among the irregular particles. Prolonged curing time promotes compressive strength because of higher hydration activity and reaction products. However, it could be noticed that the improvement in strength was obviously seen in the specimen containing higher content of M size relative to those with high content of L size, but the mixture of 50:50 ranked higher almost all curing times. These would come from two possibilities: (1) Higher content of M size offered higher reaction surface area and (2) aggregate packing and the fulfillment of the hydration reaction products. The first reason relates to higher surface area from finer grains of the M-size slag can be wetted by cement mortar, thus the reaction products [11], such as C-S-H gel, $Ca(OH)_2$ and ettringite, are literally vigorously formed and act as a binder. Along with the combination of M and L aggregates as well as these reaction products, the improved strength by bridging the existing voids was obtained. The M-size containing structure up to 50:50 had comparatively less space to be filled up. Fig. 6. (b) also pointed out that the gradual drop in strength related to amount of porosity, higher pore content, large pore size and pore connectivity altogether attributed poor load bearing. The compressive strength results were lower than [14] because of the EAF slag size used in this work was much larger, thus poor compressive strength and higher water permeability could be predicted. Nonetheless, the poor strength improvement with curing days in the monosized M was noticed. The explanation for this poorly developed strength development in the monosized M might involve two reasons: uniform mixing between cement paste and M aggregates and cracks at interparticle contact. First reason came from mixing process, at the same water to cement ratio of 0.33, aggregate to cement powder of 3:1 and similar mixing and curing practice, M aggregate was relatively fine, more irregular and most likely to have higher surface area. When cement could not cover particle surface evenly, strength development was therefore affected. Hydration products according to uneven coverage resulted in poor strength due to their formation. The bonding along interparticle was not very effective. Thus, prolonged mixing time for the monosized M might be needed. The other reason was about the contact, that is, the interfacial areas at which the coverage of cement was achieved became stress concentrator under compressive loads. Under pressure, stress pile-up at the strong bonding points while the area with weak bonding did not perform very well and eventually failed easily. Thus, the overall compressive strength was not very good even though the structure of the monosized M offered water permeability during water cure. This explanation could also apply to the poor strength improvement in the M-L bodies of 50:50, 25:75 and 0:100 during 1-14 curing days and rose after 28 days. Higher fraction of M aggregates could reflect the higher surface area necessary to be evenly covered to ensure the formation of the hydration products. Even the interlocking between M and L aggregates took part in strength, the strength improvement in the pervious concrete was most likely created from hydration. Incomplete hydration product formation could lead to unexpectedly low strength values. Such information supported the idea that prolonged mixing times should have been done when the mixture contained higher fractions of finer aggregates.

Water permeability

Water permeability of the prepared pervious concrete specimens is illustrated in Fig. 7. (a), the water flow rate ranked highest in the monosized L (100:0) specimen, followed by the monosized M (0:100) and the L-M bodies, respectively. This was caused by the size and connectivity of the pore in the monosized L (100:0), provided large connected pore channels throughout the body. According to the irregular and coarse aggregates, the packing was poor and the interlocking among large aggregates allowed more spaces, which hydration products could not fill in. Meanwhile, the monosized M was likely to facilitate water flow as seen in the monosized L but relatively narrower pore channels would be expected. The mixture of L-M bodies offered interparticle packing as seen in Fig. 3. (b), leading to water blockage and low permeability [14, 16]. This agreed with the relationship of water permeability with increasing pore contents as plotted in Fig. 7. (b).



(a)



(b)

Fig. 4. Physical properties of the prepared pervious concretes in percentage of (a) the absorbed water and (b) the calculated void content.

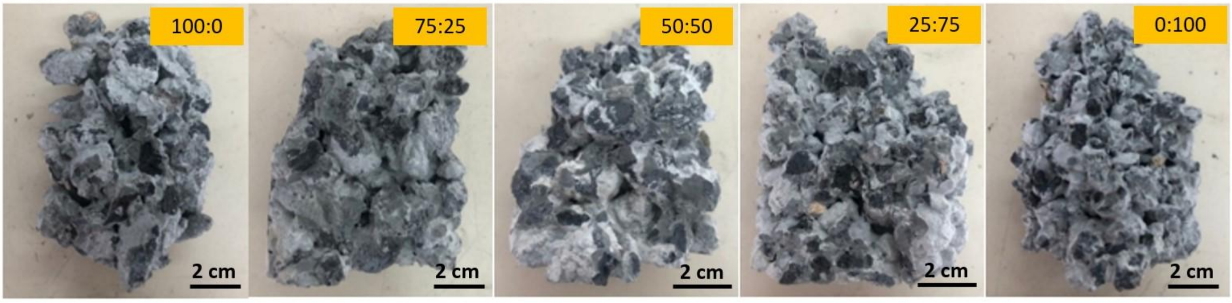
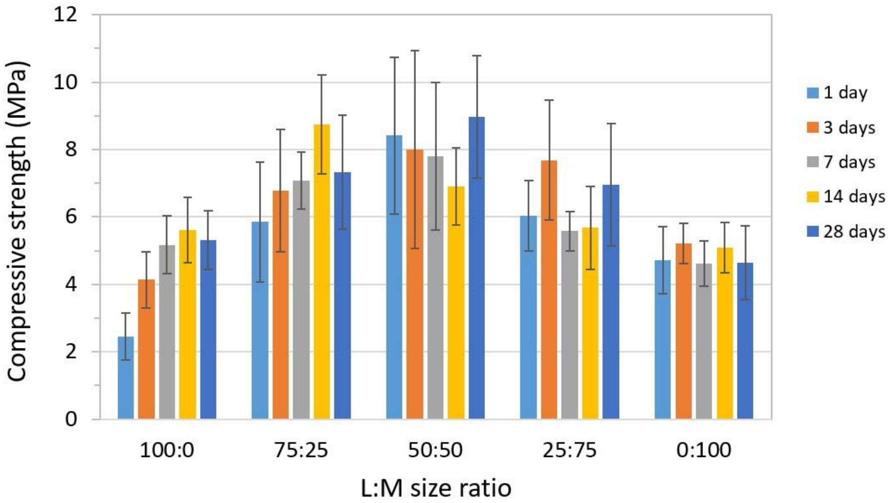
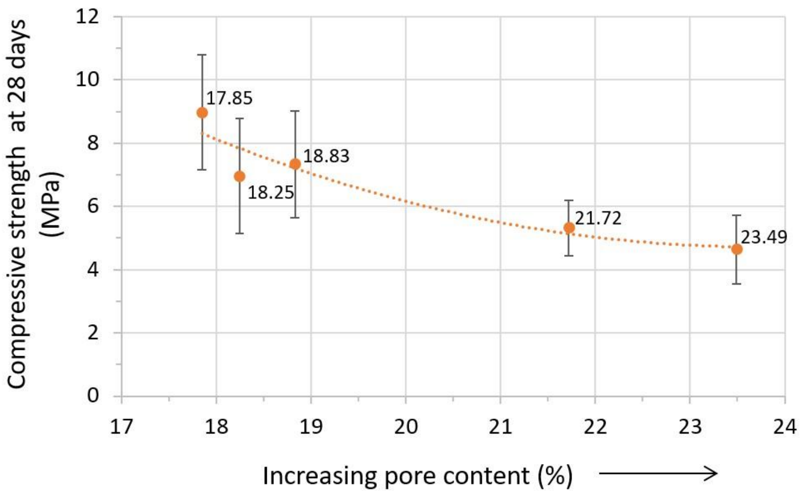


Fig. 5. Fracture surfaces of the specimens after undergoing compressive test.

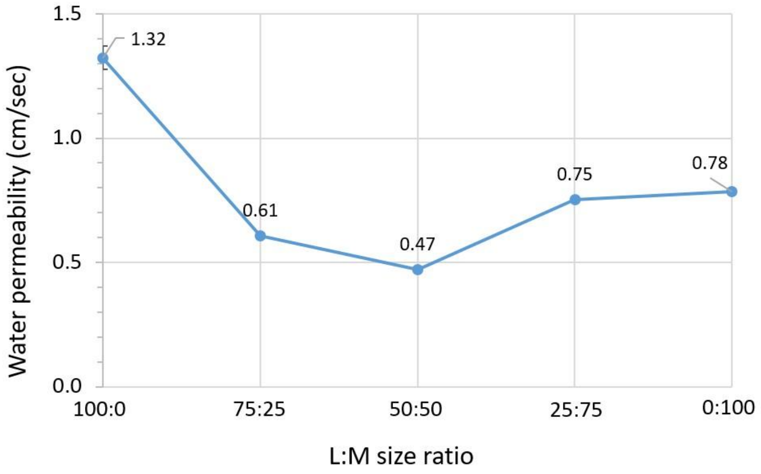


(a)

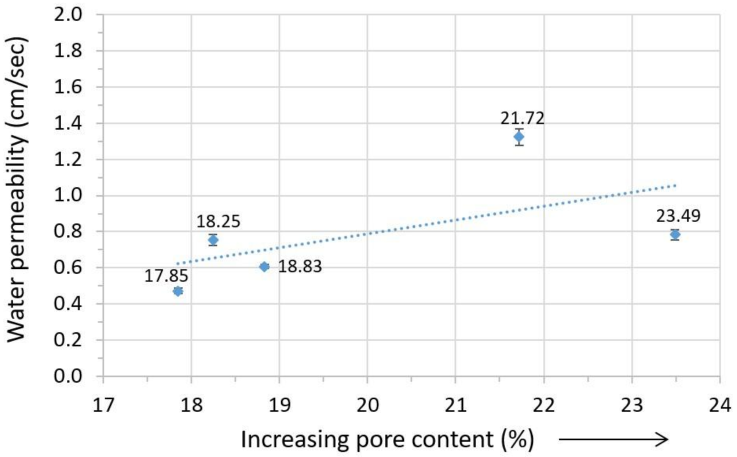


(b)

Fig. 6. (a) Variation in compressive strength of the specimens at different water curing days and (b) relationship between compressive strength at 28 days and pore content.



(a)



(b)

Fig. 7. Variation in water permeability values in the pervious concrete specimens according to (a) size ratio and (b) pore content.

Conclusion

Physical nature, mechanical strength and water permeability of the electric arc furnace (EAF) slag waste-based pervious concretes were observed. The void content of the pervious concretes depended on the size of EAF slag aggregates. The specimens containing monosized EAF slag aggregates provided higher porosity, therefore, the compressive strength values of the specimens containing monosized aggregates were relatively lower than those with the mixed size ones at all curing days. Also, the monosized aggregates offered water permeability compared to the ones with mixed sizes. The specimens with higher void content gave lower compressive strength but permitted water flow. Further study of pore connectivity and pore characteristics would be highly recommended.

Acknowledgements

The experimental work was a partial fulfillment of Bachelor degree in Materials Science, Faculty of Science, Chulalongkorn University. We would like to thank Faculty of Science for financial support and facilities. Thanks to Siam Steel Mill Services Limited for EAF slag waste material supply. Materials testing laboratory, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University was also highly appreciated for other technical supports during the preliminary study.

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