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An Overview on the Performance of Nano Silica Materials on the Properties of Porous Concrete Pavement

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Abstract – *Porous concrete technology has been used since 1970s in various parts of the United States as an option in complex drainage systems and water retention areas. Porous concrete pavements have become popular as an effective stormwater management device to control stormwater runoff in pavement. Porous concrete pavement is being used as one of the solutions to decrease the stormwater runoff by capturing and allowing rainwater to drain into the land surface. The main problem of porous concrete pavement is its strength. The objective of this paper is to review the use and performance of nano silica in porous concrete pavement and previous laboratory study on porous concrete pavement. From the literature review, it was found that the conventional porous concrete pavement does not have good strength for pavement purpose. An addition of nano-material will improve the physical and chemical properties of porous concrete pavement. To improve the strength of the porous concrete, various additives have been studied as a part of porous concrete mix and yet, the optimum condition to produce good porous concrete has still not been established. From the previous study, it was found that in preparing the porous concrete laboratory specimen, the use of standard Proctor hammer (2.5 kg) and pneumatic press (70 kPa compaction effort) resulted in the closest properties to the field porous concrete.*

Keywords: Porous, Concrete, Pavement, Nano Silica, Cement Paste

1.0 INTRODUCTION

In recent years, porous concrete pavements have become popular as an effective stormwater management device. Porous concrete pavement may be new in some areas in the world. According to Mark et al. [1], porous concrete technology has been used since 1970s in various parts of the United States as an option in complex drainage systems and water retention areas. Ghafoori and Dutta [2] found in their literature review that the earliest application of porous concrete was in the United Kingdom in 1852.The most common applications of porous concrete include driveways, parking lots, sidewalks, streets and also other low traffic volume areas [1-3]. In certain areas in highway, porous pavement has been applied to avoid accidents. There are a lot of heavy vehicles passing through highway every day. Due to this extended application, superior strength and durability become the concern of porous concrete [4]. The use of nano-materials has become popular in various fields of applications to improve and also produce materials with new functionalities. A lot of research have been done in order to explore the benefit and also to improvise the physical and chemical properties of the material itself. Nevertheless, there is still need for research to be conducted to improve the properties.

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2.0 POROUS CONCRETE PAVEMENT

Porous concrete is also known as pervious concrete, no-fines concrete and permeable concrete. Porous concrete is a special type of cementitious material composed of gap-graded aggregates, coated with a thin layer of cement paste and bonded by the cement paste layers partially being in contact [5]. Porous concrete is a concrete with continuous voids that are purposely incorporated into concrete. This type of concrete is a completely different category from conventional concrete and therefore, its physical characteristics differ greatly from those of normal concrete [6]. Fig. 1 shows a schematic diagram of porous concrete. The figure shows that porous concrete has a large size of voids. It differs with conventional concrete that has small or micro voids.

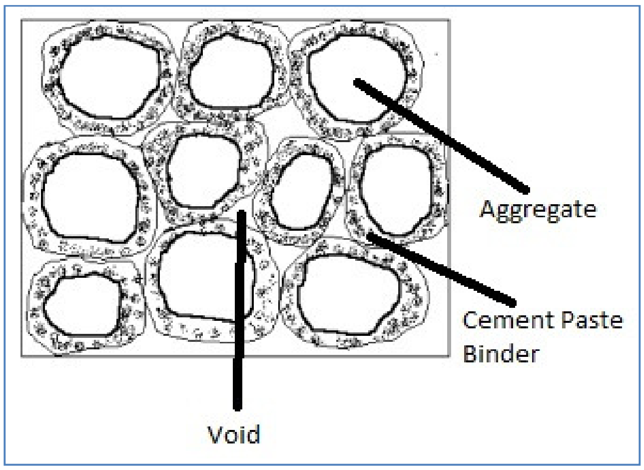

Figure 1: A schematic diagram of porous concrete [7]

Porous concrete was developed as an environmentally friendly material in the 1980s. Due to the multiple environmental benefits to control stormwater runoff, restore groundwater supplies and reduce water and soil pollution, porous concrete has been widely used in Japan, USA and Europe. Porous concrete has been utilized in road pavements due to its performances of water-permeating, water-draining and water retaining [8]. In addition, it is currently used in various applications that require noise absorption or thermal insulation [5,9,10]. A lot of studies have been conducted by other researchers and usually, the ranges of voids percentage are within 15% to 30% [5,6,8,10,11]. Porous concrete has been used for many years, but there are still many outstanding issues related to its structural performance [12]. Even though fundamental information including the influence of the water-cement (W/C) ratio ,void ratio, cement paste characteristic, volume ratio of coarse aggregate, size of coarse aggregate and strength of porous concrete have been studied, the optimum condition to produce good porous concrete has still not been established [6].

The main problem of porous concrete is its strength [13]. Recently, many studies by other researchers concentrated on ways to improve the strength of porous concrete. It has been found that the increase in porosity will decrease the compressive strength and flexural strength of the concrete [4,14,15]. Specifier's Guide for Pervious Concrete Pavement Design [16] mentioned that the structure's void of the concrete must be 15% minimum and 25% maximum. This is

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because when the structure's void in the concrete is relatively high, the strength of the concrete will decrease. As reported by Chen et al. [4], there are four major factors that will influence porous concrete strength, which are concrete porosity, water to cementitious material ratio (w/cm), cement paste characteristic, as well as size and volume content of coarse aggregate. Table 1 shows previous studies on porous concrete by other researchers. Due to voids in porous concrete, it is difficult to obtain high strength porous concrete by using common material and mixture. The ranges of concrete strength for 'high strength concrete' are 50 to 100 MPa [17]. Nevertheless, the results obtained from previous researchers are still below 50 MPa. In order to enhance the strength of the concrete, silica fume and superplasticizer can be used in the mixture's design [7]. The mixture of porous concrete needs to be modified by adding additional material (superplasticizer, steel fibre) or by replacing some percentage of cement with other materials (nano-material, silica fume).

Table 1: Previous studies on porous concrete

	Tennis *et al*., 2004 [18]	Chen *et al*., 2013 [4]	Huang *et al*., 2010 [14]	Lim *et al*., 2013 [15]
Admixture		Silica Fume + Superplasticizer & Polymer SJ-601	Polymer Latex & Fibre	Comb Polymer + Steel Fibre
Porosity of Hardened Concrete (%)	15 – 25	15 - 25	20 – 30	18.3 – 21.4
Flow Rate for Water through Porous Concrete (cm/s)	0.34	N/A	0.1 – 0.2	1.02 – 1.06
Compressive Strength (MPa)	20.5 and above	32 - 46	5 – 15	20.3 – 25.1
Flexural Strength (MPa)	3.5 and above	4.2 – 7.4	N/A	3.58 – 3.60

3.0 CEMENT PASTE BINDER

Cement paste binder is one of the important parts of porous concrete. The strength of hardened porous concrete also depends on the strength of the cement paste binder. According to Yang and Jiang [7], as hardened cement paste binder is thin, the strength of the hardened cement binder is low. They also mentioned that the existence of some pores and microcracks in the hardened cement binder will influence the strength of hardened cement paste significantly. Chindaprasirt et al. [6] also found in their literature review that the presence of void acts as weaknesses in cement matrix and produces crack formation. Cement paste binder plays an important role in porous concrete. A lot of studies have been conducted with various cement contents. Table 2 shows previous studies conducted by other researchers. From the table, it can be concluded that the increase of cement content tends to increase the compressive strength of hardened porous concrete.

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Table 2: Previous studies on various cement contents in porous concrete mix

Researchers	Aggregate (kg/m^3)	W/C Ratio	Cement (kg/m^3)	Compressive Strength (MPa)
Ibrahim *et al.*[19]	1800	0.35	250	3.45
	1600	0.35	200	2.80
	1800	0.35	150	1.83
Sumanasooriya and Neithalath [20]	1263	0.32	554	19.89
	1279	0.33	496	14.65
	1286	0.33	411	9.66
Lim *et al.*[15]	1560	0.3	367	13.90
	1560	0.3	242	8.60
Ramadhansyah *et al.* [21]	1115	0.34	450	18.03
	1450	0.33	440	14.37
	1430	0.33	400	11.82

Previously, a study to improve the strength of hardened cement paste has been conducted by other researchers. Without modifications, it is difficult to develop high strength concrete [22]. Chindaprasirt et al. [6] found in their study that the use of superplasticizer effectively reduced W/C and thus improves the strength of paste, which is highly desirable. In addition, the combination of SP and cohesive agent could produce good workability and strength properties [8]. Lim et al. [15] reported in their study that the inclusion of polymers into the mix tends to increase the compressive and flexural strength respectively. Besides that, the addition and/or replacement of silica fume (SF) [7] and nano silica [23] in cement content also strengthen the hardened cement paste.

4.0 NANO MATERIALS

Recent years, the use of nano materials has received particular interests in various fields of applications to improve the existing technologies and also produce materials with new functionalities [24]. Nano materials are used as a replacement for part of cement. The nano scale size of materials can result in significantly enhanced properties from conventional grain-size materials of the same chemical composition. Previous researches on mixing nano materials in cement based indicate that the inclusion of nano materials modifies fresh and hardened properties [25]. Nano particles have a high surface area to volume ratio and also provide high chemical reactivity [26].

Among all the nano materials, nano silica is the most broadly used material as a replacement for cement and concrete to improve their performance due to its pozzolanic reactivity besides the pore-filling effect [27]. Nano silica can act as a nano filler to fill up the spaces between particles of gel of calcium-silicate-hydrates (C-S-H). In addition, nano silica is a pozzolanic material, which has a high rate of pozzolanic reaction because of its high surface area to volume ratio and thus provides the potential for great chemical activity. The pozzolanic reaction of nano silica with calcium hydroxide will increase the amount of C-S-H, which will improve the strength and durability of the material. Nano silica reduces the setting time of mortar compared to SF. Furthermore, it also reduces the segregation and bleeding water of fresh concrete and improves the cohesiveness of the mixtures in the fresh condition [24,25]. Zhang and Islam [28] mentioned in their research that early age and 28 days strengths of cement pastes, mortars and concrete increased by using a small amount of nano silica. Table 3 shows the chemical composition of nano silica from previous research.

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Table 3: Nano silica chemical compositions

Constituent	Content			
	Senff*et al.*, 2009 [24]	Jo *et al.*, 2007 [23]	Zhang & Islam, 2012 [28]	Haruehansapong et al, 2014 [29]
SiO_2 (%)	99.4	99.9	>99.8	99.8
Na_2O (%)	0.45	-	-	-
Al_2O_3 (%)	0.075	-	-	-
Sulphate (%)	<0.1	-	-	-
Fe (ppm)	25	-	-	-
Ca (ppm)	10	-	-	-
Zn, Pb and Cu (ppm)	<0.1	-	-	-
LOI (%)	-	0.1	-	0.2

5.0 POROUS CONCRETE PAVEMENT CONTAINING NANO SILICA

The porosity of concrete tends to decrease its strength. A lot of studies have been conducted by other researchers and it was found that higher void percentage tends to decrease the strength of the harden concrete [4,7,14,15,19]. One of the ways to strengthen the porous concrete is by enhancing the strength of the cement binder. Porous concrete has a thin hardened cement paste, which will decrease the strength of the cement binder. The existence of some pores and microcracks in the hardened cement paste will influence the strength of cement paste strength [7]. Pacheco-Torgal [26] mentioned in their research that nano material allows for a significant increase in the mechanical strength of cementations composites. They will fill the voids of the C-S-H structure and lead to denser and hardened cement binder. Heikal [30] concluded in their study that composite cements containing nano silica give the optimum mechanical properties. In theory, lower voids in the hardened cement binder will result in higher strength. Indirectly, it will improve the strength of hardened cement binder and porous concrete pavement.

One of the sources of nano silica is from rice husk ash. According to Carmona [31], silica is a major inorganic element of rice husk. They also found in their literature review that 94% of rice husk contains silica. Pacheco-Torgal et al. [26] reported in their literature review that the production of nano materials can be obtained by two methods; high milling energy and chemical synthesis. Nano silica from rice husk produced from high milling energy process becomes rice husk ash. By grinding rice husk ash to nano size, it can be used as nano silica, which will then be used as cement replacement to enhance the strength of porous concrete pavement.

6.0 SPECIMEN PREPARATION FOR LABORATORY TESTING

Porous concrete pavement differs to the conventional concrete pavement. A placement of porous concrete pavement requires unique procedures compared to conventional concrete pavement. Because of that, it is important to consider the procedures used to prepare test specimens in the laboratory [32]. Several previous study have been conducted by other researchers to make a comparison of test specimen preparation techniques for porous concrete pavement. Mahboub et al. [33] conducted a study to compare the properties of porous concrete cylinders prepared using different methods. They evaluated two different methods, which are by rodding in accordance to the ASTM C192 standard and a custom built pneumatic press that applied a compaction effort of 70 kPa uniformly over the 100 mm diameter cylinders. They

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found that the cylinders compacted using pneumatic press had statistically similar properties of compressive strength, permeability and porosity as the pavement cores. The rodded specimens had compressive strength values higher than the pavement cores, and the porosity values were lower than the pavement cores. Rizvi et al. [34] conducted a research to evaluate different compaction methods for porous concrete cylinders (size: 150 mm diameter by 300 mm height) in order to find the best procedure to prepare specimens that closely represent the porous concrete in the field. They used rodding and a 2.5 kg standard Proctor hammer in their study. From the study, it was found that the specimens prepared in two layers with ten blows of a 2.5 kg Proctor hammer per layer resulted in the closest properties to the field porous concrete. However, there was no specimen similar to the field porous concrete voids, but the specimen's voids content was generally within the range values for porous concrete. Putman and Neptune [32] evaluated different porous concrete test specimen preparation techniques in an effort to produce laboratory specimens with properties similar to in-place porous concrete pavement. In their study, cylinders and slabs were casted using porous concrete from three different paving projects of different procedures. The study was based on the infiltration rate, density and porosity. Eight different methods in preparing the specimens were evaluated. These methods including the use of 15.9 mm diameter steel rod (standard tamping rod), a standard Proctor hammer (2.5 kg) and dropping the mould on a concrete surface from the height of 50 mm. The specimen types used in their study were 150 mm diameter by 300 mm height cylinder, 300 mm x 300 mm x 150 mm thickness slab, 450 mm x 450 mm x 150 mm thickness slab and 600 mm x 600 mm x 150 mm thickness slab. The result indicated that the standard Proctor hammer produced cylinders with porosity and density the closest to the porous concrete pavement in all three projects.

7.0 LABORATORY TESTING

Porous concrete pavement is one of the solutions for pavement problem. In order to apply and improve the performance of porous concrete pavement, several tests need to be conducted to evaluate the concrete. Porous concrete testing can be conducted either using in-situ testing or laboratory testing. Porous concrete laboratory testing can be divided into two categories; fresh porous concrete testing and hardened porous concrete testing. Bhutta et al. [8] in their study conducted slump and slump flow test for fresh porous concrete. This test was carried out to determine the workability of the fresh porous concrete. Hardened porous concrete can be evaluated by several tests. A previous researcher carried out a lot of tests corresponding to their objectives of study. The testing for hardened porous concrete include compressive strength test [6-8,10,11,19], flexural strength test [7,8,11], tensile splitting test [19], density test [10,19,34], porosity test [6,8,10,11,19,34], and also water permeability test [8,11,19,34]. Some researchers carried out advance testing in their study to achieve their objectives. These tests include dynamic strength test [5], strength development rate [8], fatigue test, thermal behaviour, evolution of deformation [9], sound absorption test by using impedance tube [10], water penetration coefficient, abrasion resistance, as well as freezing and thawing durability test [7].

8.0 SUMMARY

Currently, porous concrete pavement is becoming a popular choice over the world as an effective stormwater runoff management device. There are a lot of previous studies that have been conducted by other researchers in order to improve the conventional porous concrete pavement. The main problem of porous concrete pavement is its strength. Due to high voids

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content in the concrete, it is hard to produce concrete with high strength. One of the important parts in porous concrete is cement paste binder. To strengthen the cement paste binder, various types of additives have been studied by previous researchers. Even though various fundamental information has been studied, the optimum condition to produce good porous concrete has still not been established. One of the objectives of this paper is to review the use and performance of nano silica in porous concrete pavement. It was found that by incorporating nano silica in porous concrete mixture, the strength of cement paste binder would improve and indirectly would also improve the properties of porous concrete pavement. As porous concrete differs to conventional concrete, in order to study the performance of porous concrete, the best specimen preparation procedure needs to be considered. From the literature, the best procedure is by using the standard Proctor hammer (2.5 kg) and pneumatic press (70 kPa compaction effort). The right selection of procedure and testing is important in order to achieve the objectives of the study.

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