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DURABILITY PROPERTIES OF TERNARY BLENDED FLOWABLE HIGH PERFORMANCE CONCRETE CONTAINING GROUND GRANULATED BLAST FURNACE SLAG AND PULVERIZED FUEL ASH

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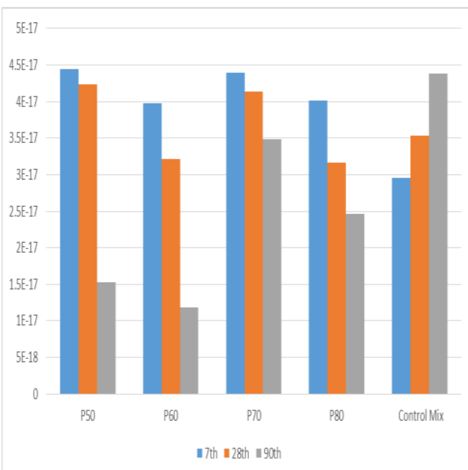
Graphical Abstract



Abstract

The use of ordinary Portland cement as the primary binder in concrete production resulted in the high carbon footprint of the concrete material which cause a great deal of environmental impacts over the years. The consumption of OPC is especially significant for high strength concrete, which require a very high cement content (more than 450 kg/m^3). Hence, supplementary cementitious materials such as ground granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA) were chosen as partial replacement materials of OPC for concrete production in the research due to their ease of availability from the steelmaking manufacturing sectors and coal-fired electricity power stations in the country. As the sustainability of concrete is also our main concern, the durability performance of flowable high performance concrete containing high volume of GGBS and PFA (50-80% replacement of OPC) has been studied in this research. Therefore, the durability properties of flowable high performance concrete had been assessed in term of air permeability, porosity, water absorption and capillary action. From the results of assessment, all ternary blended concrete mixes exhibited better durability performances than control OPC concrete at later ages due to formation of denser microstructure by pozzolanic reaction of GGBS and PFA. It is concluded that the mix proportion of flowable high performance concrete production with 60% replacement of OPC by GGBS and PFA has the optimum durability performances than OPC concrete.

Keywords: Ternary blended concrete, GGBS, PFA, high performance concrete, durability properties

Abstrak

Penggunaan simen Portland biasa (OPC) sebagai pengikat utama dalam penghasilan konkrit telah membawa kesan hasilan bahan konkrit yang mempunyai jejak karbon yang tinggi serta memberi kesan negatif kepada alam sekitar selama bertahun-tahun. Pengambilan OPC amat signifikan untuk penghasilan bahan konkrit yang yang mempunyai kekuatan tinggi dengan kandungan simen yang sangat tinggi (melebihi 450 kg/m^3). Oleh itu, bahan-bahan sampingan bersimen seperti *ground granulated blast furnace slag* (GGBS) dan *pulverized fuel ash* (PFA) telah digunakan sebagai sebahagian bahan ganti OPC dalam penghasilan konkrit kajian ini kerana kebolehsediaan GGBS dan PFA dari sektor pembuatan keluli dan stesen kuasa elektrik arang batu dalam negara ini. Oleh sebab kemampanan konkrit merupakan bimbangan utama kami, prestasi ketahanan konkrit mengandungi GGBS dan PFA yang tinggi (50-80% penggantian OPC) telah dikaji. Maka, sifat-sifat ketahanan bagi konkrit yang berprestasi tinggi dan mempunyai kebolehaliran tinggi telah dinilai dari segi kadar resapan udara, keliangan, penyerapan air dan tindakan kapilari. Daripada hasil penilaian kami, semua konkrit campuran pertigaan telah mempamerkan pretasi ketahanan yang lebih baik daripada konkrit OPC kerana pembentukan mikrostruktur yang lebih padat dengan tindak balas pozolanik GGBS dan PFA. Daripada kajian ini, kadar campuran untuk penghasilan konkrit yang berprestasi tinggi dan mempunyai kebolehaliran tinggi ialah campuran 60% penggantian OPC oleh GGBS dan PFA. Kadar campuran ini mempunyai prestasi yang optimum atas sifat-sifat ketahanan berbanding dengan konkrit OPC.

Kata kunci: Konkrit campuran pertigaan, GGBS, PFA, konkrit berpretasi tinggi, pretasi ketahanan

1.0 INTRODUCTION

High demand of Portland cement (OPC) from the market has led to high level of production of cement from limestone. During the production of Portland cement, carbon dioxide, CO_2 would emitted into the environment, which causing greenhouse effect, air pollution and global warming. High level of CO_2 emission has increased year by year due to rapid development of construction all around the world. Hence, OPC has a very high carbon footprint that gives unexpectable impact to the environment, and this issue must be took seriously.

Ordinary Portland cement is a fine powder that originated from limestone that used as a construction material over centuries. It is widely used due to low cost and widespread availability of the limestone, shales and other materials that utilized to produce OPC. However, it is containing hazardous components that harmful to human beings and mainly to the environment. During the cement manufacturing process, calcium carbonate is heated to produce lime and carbon dioxide, CO_2 gas that released to the atmosphere. It is recorded that 900 kg of CO_2 gas will be produced for every 1 ton of cement produced [1]. So, cement industries is known as the second largest emitter of CO_2 gas other than gas fuel combustion during energy generation. The cement production contributes 5% of global man-made CO_2 gas emissions in which 50% from its chemical processes, 40% of it from the fuel combustion and 10% from the electricity generation [2, 3]. Besides, other polluting substances emitted to the atmosphere including dust, carbon oxide (CO), nitrogen oxide (NO_2) and sulphur dioxide (SO_2), 0.27-2273 mg/Nm^3, 200-2000 mg/Nm^3, 145-2040 mg/Nm^3, up to 4837 mg/Nm^3 respectively.

Hence, the effective way to decrease the encounter the high carbon emission by conventional Portland cement production, ternary blended concrete has introduced. Ternary blended concrete is fabricated using industrial by-product as partial replacement binders or substitute of OPC which exhibited similar or better mechanical, physical and durability properties as compared to OPC concrete [4]. Ground granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA) were chosen due to their ease of availability from the steelmaking manufacturing sectors and coal-fired electricity power stations that produced huge amount of these waste annually which can be utilized in mass production of ternary blended concrete in the country as compared to other pozzolans.

The utilization of these two supplementary cementitious materials is due to their ability to react with OPC by producing secondary hydrated products, calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-S-H) by a chemical reaction, called pozzolanic reaction which similar to the $Ca(OH)_2$ from the cement hydration will be produced. The hydration process of ternary blended concrete are divided into primary hydration by OPC and GGBS, pozzolanic reaction of GGBS and PFA as the secondary hydration. They reacts with the $Ca(OH)_2$ produced by cement hydration to form C-S-H bond and C-A-S-H bond that gives a denser microstructure than conventional OPC concrete [4-7]. The denser microstructure has improved the durability properties of ternary blended concrete in term of permeability, porosity, sulphate attack and chloride ingress [8-11].

The formation of C-S-H produced denser microstructure that harder for sulfate and chloride to penetrate into concrete structure. So, the sulfate and chloride attack is lower when the permeability of the concrete is lower. GGBS and PFA consumes great quantity of $Ca(OH)_2$ which necessary for sulfate attack [8]. So the possibility of aggressive ion penetration into concrete is lower compared to OPC concrete.

Due to the benefits of utilization of GGBS and PFA to the concrete, ternary blended high performance concrete can only be produced with the characteristic of high strength and improved durability properties. However, several researches had discussed the influences of incorporation of GGBS and PFA in ternary blended system on the mechanical performances of resulted concrete at various replacement level whereas the durability properties such as permeability, water absorption, porosity and capillary action of GGBS-PFA concrete at high OPC replacement level is barely discussed [5-6, 12-13].

Hence, this paper is focus on discussing the influences of high volume of GGBS-PFA ternary blended system on the durability properties of flowable high performance concrete.

2.0 METHODOLOGY

2.1 Materials

The materials used as binder for the mix design of ternary blended concrete are Portland cement, GGBS and PFA, while fine aggregates and coarse aggregates are also added. There are two chemical admixtures are used to serve as high range water reducer and high range water reducing retarder. The chemical composition of birders are showed in Table 1.

Table 1 Chemical composition of binders

Chemical (%)	OPC	GGBS	PFA
SiO_2	22.40	32.43	43.22
Al_2O_3	3.60	11.92	17.61
Fe_2O_3	2.9	0.28	13.73
CaO	65.60	37.68	11.28
MgO	1.50	4.52	5.94
K_2O	0.34	0.32	0.36
Na_2O	-	0.23	Trace
P_2O_5	0.06	0.01	0.01
TiO_2	0.17	0.45	0.88
Loss of ignition	2.53	-	1.80

2.1.1 Portland Cement (OPC)

Portland cement is used as the main binder for the concrete mix, is often called as OPC where undergoes hydration when reacts with water to forms insoluble calcium hydroxide, $Ca(OH)_2$ and primary C-S-H thus hardening process occurs to become hardened concrete. The specific gravity of the Portland cement is 3.15. The typical constituent of Portland cement including calcium oxide (CaO), Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3) and sulfur (VI) oxide (SO_3).

2.1.2 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag (GGBS) is the by-product of steel and iron making process and is obtained during the mixing of iron ore, coke and limestone in the blast furnace at the temperature 1500 °C. The GGBS used is obtained from local supplier with the specific gravity of 2.86 and is in granulated form, the specific surface area of GGBS after grinded is found to be an average of 4250 cm^2/g where would significantly improve the performance of concrete (4000 cm^2/g to 6000 cm^2/g). GGBS is widely used in the concrete industry as a supplementary cementitious material to partially replace Portland cement in concrete mix due its similar level of CaO content that undergoes hydration when reacts with water. In this study, GGBS was used as primary binder to substitute OPC content of concrete. The GGBS used is showed in Figure 1.

Figure 1 GGBS used in this study

2.1.3 Pulverized Fuel Ash (PFA)

Pulverized fuel ash (PFA), also known as fly ash, by product from the burning of pulverized coal in coal-fired electricity power stations. Utilization of fly ash in concrete mix is due to its extremely fine particles and glassy spheres that are similar to the cement in appearance. The specific surface area of PFA particles is typically 3000-5000 cm^2/g and its specific gravity is 2.80. The fineness of fly ash has offered a better bond formation in the microstructure of the concrete. Besides, use of fly ash results in improve rheology that reduce water demand of concrete which reduces the possibility of bleeding of fresh concrete, hence lower water-to-binder (w/b) ratio can be achieved with a fixed workability. In this study, PFA was used with GGBS in a fixed ratio as substitution material to OPC. The PFA used is showed in Figure 2.

Figure 2 PFA used in the study

2.1.4 Aggregate and Water

Fine aggregates are obtained from the quarzitic natural river in uncrushed manner with the maximum size about 5 mm and specific gravity of 2.63. The fine aggregates is heated to saturated surface dried so it can be ready used for mix. The coarse aggregates is choose to be the maximum size of 5-10 mm which passed through 10 mm sieve and retained on the 5mm sieve. The specific gravity of coarse aggregates is 2.65. Then, the coarse aggregates were washed and dried to remove unnecessary debris. Local water source is obtained as the mixing water.

2.1.5 Chemical Admixture

There are two chemical admixtures, with commercial designation of ACE 8703 and ACE 8109 are added into the mixture during mixing process together with water. The ACE 8703 is served as the high range water reducing retarder in order to achieve required flow without addition of extra water; while the ACE 8109 is the high range water reducer to increase the strength development of the ternary blended concrete in order to achieve the target strength in the early age. The dosage of the SP for each design is showed in the Table 2. The slump of the fresh concrete is adjusted by addition of extra dosage of chemical admixtures by 0.05% to the total binder mass in order to achieve the desired flow of concrete.

2.2 Methods

2.2.1 Mixture Proportioning and Mixing

In this study, the flowable high performance concretes were prepared at different replacement level, that varies from 50% to 80% of GGBS and PFA at fixed ratio of 4:1 and the water to binder ratio was constant at 0.35. A total of 5 mix designs, including one reference OPC mix were studied, and the mix proportions of concretes, dosage of each chemical admixture and achieved flow were recorded in Table 2.

2.2.2 Mixing, forming and Curing

Every batch of flowable high performance concrete was mixed homogeneously using an epicyclic mechanical mixer with the specification prescribed in ASTM C305-14 [14]. The materials were first measured by electronic balance according to the mix design, the dry mixed in the epicyclic mechanical mixer for 10 minutes at a low mixing speed before the mixing water was added to the mixture. Three quarter of mixing water was added to the mixtures, then mixing for another 2 minutes at medium speed. After that, the chemical admixtures were then added to the mixtures together with the remaining amount of water, the mixing process was continued for another 2 minutes. After that, the slump of fresh concrete mixtures was tested following the prescricption stated in BS EN 12350-4:2009 [15] and ASTM 143/143M [16]. The flow of mixture was adjusted to by addition of extra dose of chemical admixture until the desired flow achieved. Before placing into the moulds prepared, the fresh mixtures was mixed for another 2 minutes. So, the concrete mixtures were allowed to set in the moulds for 24 hours before removal for water curing as prescibed in ASTM C192/C 192M-16a [17].

2.2.3 Water Absorption

The water absorption of each design of flowable high performance concrete was tested by preparing cylindrical specimens with a dimension of 75 mm Ø x 100 mm for each testing age. The specimens were then dried in the oven for 72 ± 2 hours when the testing age reached. The samples were allowed to cool down for 24 ± 0.5 hours before their dry weight were recorded. After that, the samples are immediately completely immersed in water where water covered the specimen with 25 ± 5 mm. The samples are leaved for water absorption for 30 ± 0.5 min. The saturated weight of each sample is measured and recorded. Thus, the water absorption of each sample was calculated as prescribed in BS 1881-122 [18].

2.2.4 Porosity

The porosity of flowable high performance concrete was determined using cylindrical specimens with a dimension of 50mm Ø x 50 mm for each mix design of concrete. The specimens were dried in the oven for 72 ± 2 hours and then allowed to cool down for 24 ± 0.5 hours before their dried mass were recorded. The specimens were placed into a desiccator filling with water which was sealed tightly with grease. The saturated mass of specimens were recorded, and the porosity of specimens for each mix design at different testing age were calculated as following formula.

$$\text{Porosity} = \frac{m_{sat} - m_{dried}}{m_{sat} - m_{water}} \; x \; 100 \qquad (1)$$

Where
m_{sat} is mass saturated specimen
m_{dried} is dried mass of specimen
M_{water} is mass of saturated specimen in water

2.2.5 Intrinsic Permeability

The intrinsic permeability of each mix design of concrete at different testing ages was determined by cylindrical specimens with a dimension of 50mm Ø x 50 mm. The specimens were previously oven dried for 72 ± 2 hours and then allowed to cool down for 24 ± 0.5 hours. The testing method for determination of intrinsic permeability of specimens was following the method introduced by Cabrera and Lynsdale [19].

Table 2 Mix design for each concrete mix in kg/m³

Mix code	OPC (kg/m³)	GGBS (kg/m³)	PFA (kg/m³)	Sand (kg/m³)	Coarse aggregate (kg/m³)	Water (kg/m³)	w/b ratio	Admixture (Litre) ACE 8703	Admixture (Litre) ACE 8109	Flow (mm)
control	487	-	-	964	818	170	0.35	4.62	6.57	460
P50	244	195	49	965	799	170	0.35	3.65	5.60	500
P60	195	234	58	963	798	170	0.35	3.65	4.89	490
P70	146	273	68	964	793	170	0.35	3.65	4.82	400
P80	97	312	78	964	789	170	0.35	1.95	2.73	500

2.2.6 Capillary Action

The capillary action of each concrete design was measured by preparing prisms with a dimension of 40 x 40 x 160 mm. The prisms were first cured for 7 days and placed into oven until a constant mass of prisms were achieved, then the dried mass was recorded. After that, the capillary action of specimens was measured for first 8 hours and for following every 24 hours up to 21 days.

3.0 RESULTS AND DISCUSSION

3.1 Water Absorption

In Figure 3, the water absorption of ternary blended concrete mix at all level of replacement, 50% - 80% by GGBS and PFA were recorded and plotted, exhibited lesser water absorption than OPC sample as the reference mix. All samples obtained a reduction of water absorption value over the time after long term curing process. At early age, OPC has highest water absorption than other ternary blended concrete samples, which is 2.26% and the lowest value, 0.63% for P60. These results indicated that ternary blended concrete containing high volume of GGBS and PFA can possesses less water absorption rate than OPC concrete. However, P60 with 60% of replacement level by GGBS and PFA with the percentage of 48% and 12% by the total mass of binders has the lowest water absorption value at all age. This is due to less void volume of the pore structure of concrete by means of formation of C-S-H bond and C-A-S-H bond from the reaction of GGBS and PFA with the $Ca(OH)_2$ produced from hydration of Portland cement which has enhance the resistance for water penetration [3]. The higher water absorption value of P70 and P80 might because of less formation of hydrated products by cement hydration and more relying on pozzolanic reaction of GGBS and PFA for the microstructure densification. At the 90th day, the water absorption value of P60 has recorded as 0.43% which is almost four times lesser than OPC sample with the value of 1.67%. This results is supported by the study stated that ideal fly ash replacement level is 15% to 25% for high strength concrete [20]. The surface water absorption of the concrete is lowest when the replacement level is 60%-70%.

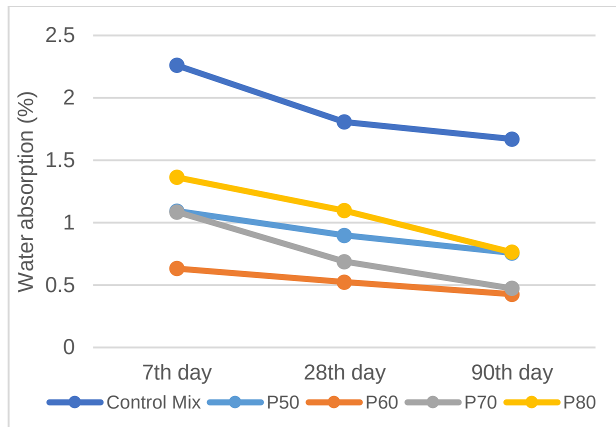


Figure 3 Water absorption of concrete

3.2 Porosity

Figure 4 showed the porosity value of all of the ternary blended concrete at all testing ages. At the early age, all of the ternary blended concrete samples has lower porosity than OPC sample, except P50 with a slight higher porosity that recorded as 10.66% compared with 10.48% for OPC sample. As the age of concrete grow, porosity of all samples were reduced due to further hydration of binders. For decrease in porosity of ternary blended concrete samples is due to the secondary hydration of supplementary cementitious materials, GGBS and PFA which has finer particles than Portland cement that contribute to the formation of C-S-H and C-S-A-H bonds that filling the pores between of the hydrated product from the primary hydration of Portland cement. Besides, P50 has higher porosity than those with higher replacement level of Portland cement at all testing age. During 90th day testing age, the total porosity of P50 is higher than other ternary blended samples which possess 7.69%, but lower than OPC sample with 9.76%. Hence, it showed that ternary blended concrete has better porosity resistance than OPC sample, and the replacement level higher than 50% replacement possess better porosity performance. Among the all the ternary blended samples, P60 obtained the lowest porosity value at all testing age which is only 4.36% that is 55% lesser than reference mix which is 9.76%. The results is showed in Figure 4. Hence, the porosity of concrete is lower when ternary blended concrete containing 60-80% GGBS and PFA.

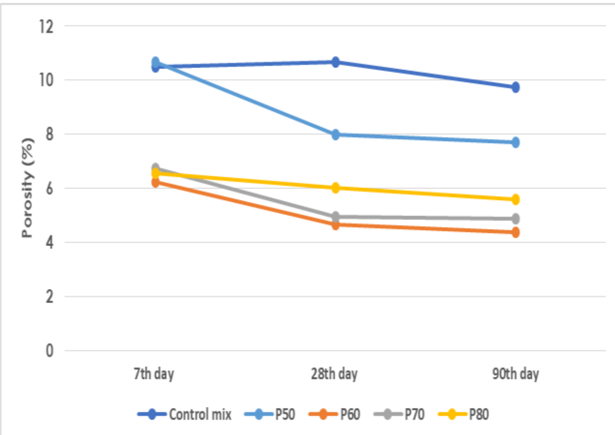


Figure 4 Porosity of concrete

3.3 Intrinsic Permeability

All the ternary blended concrete samples had recorded that the air permeability performance is better than OPC concrete at the final age as shown in Figure 5. Although, the OPC sample exhibited highest air permeability resistance at the early age (7th day) among all the sample, but the air permeability of OPC sample was recorded to be lowest at 90th day compared to other ternary blended concrete sample, it showed a significant increase of reading after a long term curing up to 90 days. This phenomenon showed that the hydration rate of OPC sample is faster than those ternary blended concrete sample regardless the replacement level at the early age. A denser concrete was formed by OPC sample due to the formation of hydrated product, calcium hydroxide. $Ca(OH)_2$ and primary C-S-H bonds that forms the pore structure of the OPC concrete while the ternary blended concrete containing less volume of cement to contribute to hydration of cement. Among the ternary blended samples, the P50 sample has the lowest permeability at the early age whereas P60 has highest among the ternary blended concrete samples. At later age, those ternary blended concrete samples has lower air permeability than OPC sample due to the pozzolanic reaction of GGBS and PFA reacts with $Ca(OH)_2$ that produced from cement hydration to form stable calcium silicate hydrate or C-S-H gel that filling the pore of microstructure of ternary blended concrete or reduce in the pore size within pore structure which has increase the permeability resistance [21]. At 90th day testing age, P60 was recorded as the ternary blended sample with highest air permeability resistance. Though P70 and P80 were higher content of GGBS and PFA which might contribute for pozzolanic reaction that to develop the microstructure of the concrete, but low content of Portland cement was gives rise of low percentage of $Ca(OH)_2$ content which can be used for formation of C-S-H and C-A-S-H gel. The formation of these bond by GGBS and PFA consumes a larger quantity of $Ca(OH)_2$. Hence, P50 and P60 are less permeable than P70 and P80. The air permeability of P50 and P60 at 90th day is 1.53×10^{-17} m^2 and 1.18×10^{-17} m^2 respectively. The value of P50 and P60 is 65-73% lower than OPC sample. The optimum percentage of replacement is 50-60% in term of the permeability performance of the concrete.

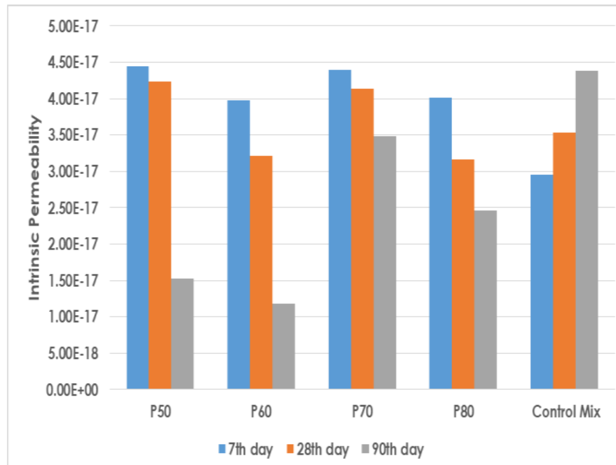


Figure 5 Intrinsic permeability of concrete

3.4 Capillary Action

The results of capillary action of all samples were showed on the Figure 6 at below using their cumulative weight gain against the square root of time by hours. All samples experienced rapid weight gain in first 8 hours, especially at the 2nd hour to 3rd hour, that was a drastically gain in weight. Same phenomenon happened during the 2nd day to 3rd day for all sample while the OPC sample and P50 showed a significant jump in the weight compared to other ternary blended samples which are steadier with a gain of less than 0.1%. The high cumulative weight gain in first 4 hours can be interpreted that water was being absorbs by the concrete where filling the bigger capillary pores with higher pore diameter within those specimens and then the increase of the cumulative weight gain becoming steady because of macro-pores within the microstructure of concrete was completely filled by water, the later water absorption is filling those finer and smaller micro-pores up to 14th day [22]. The cumulative weight gain became more linear for all concrete samples after 14 days. The OPC sample showed a steeper gradient of cumulative weight gain over time due to the existence of more capillary macro-pores than ternary blended concrete with high replacement level. In the other words, this indicates that ternary blended concrete containing high volume of GGBS and PFA has more micro-pores than macro-pores compared with OPC sample. Hence, the presence of GGBS and PFA do reduces the pore size of the capillary pores within the microstructure of the concrete.

From the Figure 6, the cumulative weight gain of OPC sample at the end of the capillary action test is relatively highest with the reading of 42.83 kg/m^3 which is 27% higher than P50 and 56-59% higher than other ternary blended concrete samples. Among those ternary blended concrete, P50 has steeper increase in the gradient of the cumulative weight gain of concrete over the period comparing with the other ternary blended samples, P60, P70 and P80. The cumulative weight of P50 at last testing age is 44% higher than P60, the lowest cumulative weight gain at the moment. This indicates that the replacement of Portland cement by GGBS and PFA more than 60% has significantly improve the capillary penetration resistance of concrete. The replacement of Portland cement by GGBS and PFA up to 60% has a better capillary penetration resistance comparing with other samples which is only 17.58 kg/m^3. The capillary transport of P60 is 2.4 times better than OPC samples at 90th day.

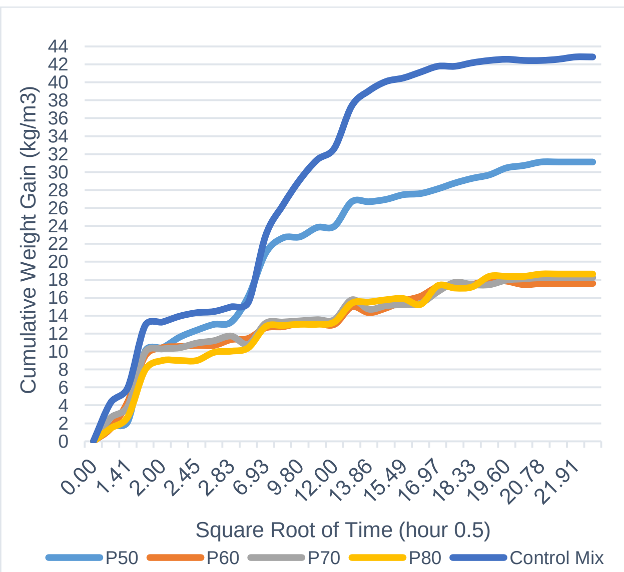


Figure 6 Capillary action of concrete

4.0 CONCLUSION

Based on the analysis of data obtained from laboratory investigation done on the durability properties of high performance concrete mix design with various percentages of cement replacement by GGBS and PFA, it can be concluded that the concrete with replacement level more than 50% has significant improvement in the durability performances, as further increase in substitution level has led to a perceivable drop of performance when up to 80% of GGBS-PFA content were used. It is attributed to insufficient of $Ca(OH)_2$ from cement hydration provided for pozzolanic reaction of GGBS and PFA to produce more secondary C-S-H and C-A-S-H bonds that refined the pore structure of concrete, which reduced the volume of both micro and macro pores. Therefore, a flowable high performance concrete with optimum performance in term of permeability, porosity, water absorption and capillary absorption can be obtained at 60% of GGBS-PFA content.

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