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Strength, abrasion resistance and permeability of artificial fly-ash aggregate pervious concrete

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ABSTRACT

The objective of this study is to utilize artificial cold bonded fly ash aggregate (AFA) in pervious concrete to produce a sustainable, and permeable concrete. The AFA were manufactured through cold bonding pelletization of fly ash (90 %) and Portland cement (10 %) in an inclined pan at ambient temperature. In this study, pervious concrete is manufactured by replacing the natural aggregates (NA) with AFA in five levels of replacements 0–100% with 25 % increments of the total aggregate's volume. Two different concrete series were manufactured at 0.27 and 0.32 water-to-cement ratios (w/c). Totally, 10 pervious concretes were manufactured in this study. The utilized NA and AFA were uniformly graded and ranged 12.5 mm to 8 mm. In this study, the dry density and content of voids were determined. Furthermore, for the produced pervious concretes some tests were conducted such as compressive strength, splitting tensile, permeability and abrasion resistance. Besides, GLM-ANOVA as a statistical tool was employed to examine the effective parameter(s) on the properties of pervious concrete made using AFA. The results showed that with replacing the natural aggregate with 100 % AFA, the dry density of pervious concretes has decreased up to 22.4 % and the content of void and abrasion value has increased up to 20.8 %, and 153.8 %, respectively, for 0.27 w/c. In addition, the full replacement of NA with AFA resulted in a decrease of 51.5 % and 57.2 % in compressive strength and splitting tensile values made with w/c of 0.27. While, utilizing AFA significantly enhanced the permeability coefficient of the pervious concrete reaching maximum value of 10.27 *mm/sec* at w/c of 0.32.

1. Introduction

In the recent years, the use eco-friendly materials in building industry has become crucial. The employment of supplementary cementitious materials such as fly ash in the production of concrete as cement replacement or as aggregates can potentially result in eco-friendly concrete [1–4]. Artificial cold bonded fly ash aggregates (AFA) can be utilized to produce eco-friendly concrete [5–7]. In most of the developed countries, a large amount of fly ash is accumulated as a byproduct material causing a major environmental problem due to the scarcity of landfill sites. Although tons of fly ash powder are generated from (fired thermal coal) power plants all over the world annually, only a small portion of fly ash is used in the construction industry [7]. Anjani and Vikranth [8] stated that the global fly ash production is about 460 Million tons annually. However, the utilization of fly ash is only 25 % of the global production. For instance, India and China as top producers of fly ash have a utilization rate less than 50 %, while Denmark, Italy and Netherlands have a fly ash utilization rate 100 %. One consuming technique of fly ash is the manufacturing of AFA by a positive influencing on the environment and least energy feeding by the pelletization of fly ash elements by a cold-bonded procedure, while the wetting agent is water and reacting as

Abbreviations: AFA, artificial cold bonded fly ash aggregate; NA, natural aggregates; w/c, water-to-cement ratio; a/c, aggregate-to-cement ratio; ASTM, American society for testing and materials; ITZ, interfacial transition zone; GLM-ANOV, Ageneral linear model-analysis of variance.

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coagulant, thus the wet blend would be pelletized in a sloped rotating pan [7,9,10]. Therefore, this can be considered as another environmental benefit of the cold-bonded pelletizing process, because the AFA made with this way are composed of 90 % fly ash by weight [11]. This type of aggregate is originally lighter in weight than natural aggregates (NA) and has been utilized in the producing of normal concrete [12], self compacted concrete [13], and high strength concrete [14]. In the literature, there have been some studies deal with pervious concrete produced with the different type of aggregate but there is no study about using the AFA in the manufacturing of pervious concrete.

Pervious concrete is a unique type of concrete that consists of a gap-graded system. Commonly it has a slump value near to zero and comprises the cement, uniformly graded aggregate, water and usually eliminate fine materials. The mixture of the constituents will make a hardened matrix that permits rainwater to easily pass. The permeability rate of water of this concrete usually changes between 1.4-12.2 *mm/s*, the compressive strength and water-to-cement ratio (w/c) range from 2.8 to 28 *MPa* and 0.26 to 0.40, respectively. Besides, the content of void is in the range 15–30 % [15–17]. In general, in pervious concretes the content of the cementitious material is between 270 and 415 kg/m^3 [15,18]. The ability to transport a huge volume of water through its highly interconnected pores into the ground is the main benefit and property offered by pervious concrete, as a result replenishing underground water and decreasing or removing problems linked with rain water [16,19]. Pervious concrete is considered as a best management practice because of its capability to reduce excessive storm-water runoff [20]. Unlike conventional concrete, the properties of the materials that utilized in pervious concrete are highly dependent on both concrete materials and casting methods [21]. Pervious concrete was utilized for above 30 years in many regions in all over the world, particularly in the United Kingdom and the United States [22]. It is applicable to the construction of car parks, lightweight transportation, walkways, tennis courts, greenhouses, and some other areas [16,23–26]. Reducing urban heat-island effects is another environmental benefit that presented with pervious concrete [16,27–29]. For producing pervious concrete usually a uniformly graded aggregates are used. This gap graded system is also significant to reduce tire pavement interaction noise and water pollution [15,30,31]. Pervious concrete is usually lower in strength and durability properties than conventional concrete as a result of its high porosity content [31]. Therefore, the main lack of the pervious concrete is its lower compressive and tensile strengths and clogging by fine materials compared to conventional concrete and the cost of its maintenance and cleaning is high. Besides, resistance to freeze-thaw cycles and deicing chemical attack are more critical than conventional concrete [32]. The important parameter such as content of void, w/c, paste matrix, and size of coarse aggregates have effects on the characteristics of the pervious concrete [22,33,34]. The cement paste plays a great role for increasing the strength of pervious concrete [35].

In the production of pervious concrete, beside NA different types of aggregates has been used. Light weight aggregates has been used in pervious concrete by Zaetang et al. [36] investigated the effect of the pumice and diatomite as natural and recycled light weight aggregates on the properties of pervious concrete. Some other researchers utilized recycled concrete aggregates [37] and waste materials [38,39] into pervious concrete to keep natural resources and produce a sustainable pervious concrete. Pervious concrete can be considered as one of the best materials utilized in sustainable drainage system. For the sake of reducing the consumption of raw materials and minimze the negative impact of concrete on the environment, the use of waste materials in concrete can be employed in devloping sustainable drainage system. Thus, sustainable pervious concrete made by substituting NA with waste aggregates could be a good solution. Khankhaje et al. [40] have studied the utilization of waste aggregate from palm oil industry in pervious concrete and the waste aggregate was lighter in weight compared to NA. He stated that a pervious concrete with a compressive strength of 13 *MPa* could be adequate to support parking lots even when the concrete subjected to light vehicular loads and a void content 20 % permit the water to percolate through the pavement structure. Hence, the target performances of the produced pervious concrete in this experimental work was a compressive strength of 13 *MPa* and a void content of 20 % that can be applicable for parking lots.

Research studies tackling the mechanical performance and durability behavior of pervious concrete incorporating artificial cold bonded AFA as aggregates are very limited. Therefore, the main purpose of this study is to investigate the mechanical properties and durability aspects of pervious concretes by replacing NA with artificial AFA to produce a sustainable pervious concrete. Following the production of AFA, the NA and AFA were screened to obtain the uniformly graded aggregate in the range of 8 to 12.5 *mm*. In this study, two different mix series with w/c of 0.27 and 0.32 were designed and five substitution levels of 0–100% with 25 % increments of the total aggregate content were selected.

A total of 10 pervious concrete mixes were produced and dry density, content of void, compressive strength, splitting tensile strength, permeability and abrasion resistance of the produced concrete were experimentally determined after for period of 28 day water cure.

2. Experimental study

2.1. Materials

2.1.1. Cement

The constituent material used in manufacturing pervious concrete was Portland cement (CEM I 42.5R), uniformly graded Natural aggregate (NA) and artificial cold bonded fly ash aggregate (AFA). Same cement was also employed to manufacture

Table 1
Chemical configurations and physical characteristics of Portland cement and Fly Ash.

Chemical analysis (%)	Portland cement	FLY Ash
CaO	62.12	2.24
SiO_2	19.69	57.2
Al_2O_3	5.16	24.4
Fe_2O_3	2.88	7.1
MgO	1.17	2.4
SO_3	2.63	0.29
K_2O	0.88	3.37
Na_2O	0.17	0.38
Free lime	1.91	–
Loss on ignition	2.99	1.52
Insoluble residue	0.16	–
Specific gravity	3.15	2.04
Specific surface area (m^2/kg)	394*	379

the artificial AFA aggregates. The chemical compositions and physical characteristics of the Portland cement and Fly Ash are shown in Table 1.

Moreover, the chemical composition of the Portland cement and Fly Ash has been analyzed by X-Ray Diffraction (XRD). Regarding the physical properties that have measured in this study, specific gravity was measured according to ASTM_C188 – 17 [41], and Blain fineness was measured referring to DIN EN 196–6 [42].

2.1.2. Aggregates

The pervious concrete was produced by using uniformly graded aggregates passing through 12.5 *mm* and retaining on 8 *mm* sieve to achieve adequate permeability. Two types of aggregates were employed in this study. The first type is natural aggregates (NA) with the specific gravity of 2.72 and water absorption of 0.92 %. While, the second types, is artificial fly ash aggregates (AFA) usually called as cold bonded fly ash aggregates which is produced using fly ash and cement.

In this study, the AFA was made through the cold bonding pelletization method. In this method 10 % of cement and 90 % of fly ash as dry powders were added to a mixer's pan-like pelletizeation disk. The dry powders were mixed in the pelletizer disk with a pot width of 800 *mm* and a depth of 350 *mm* at room temperature (see Fig. 1). In general, the time required for the pelletization process was estimated at about 20 *min*. For the initial 10 *min* of the AFA making process, the water was added to the powder to play as a coagulant. The quantity of water used for spraying estimated as 22 % of the dry powder (by mass). Thereafter, the rotation of the pelletizing disk was continued to complete the agglomeration process to get dense and stiff spherical fresh pellets during the final 10 *min* as shown in Fig. 2. Then, fresh particles were kept in closed bags and kept for four weeks in room temperature.

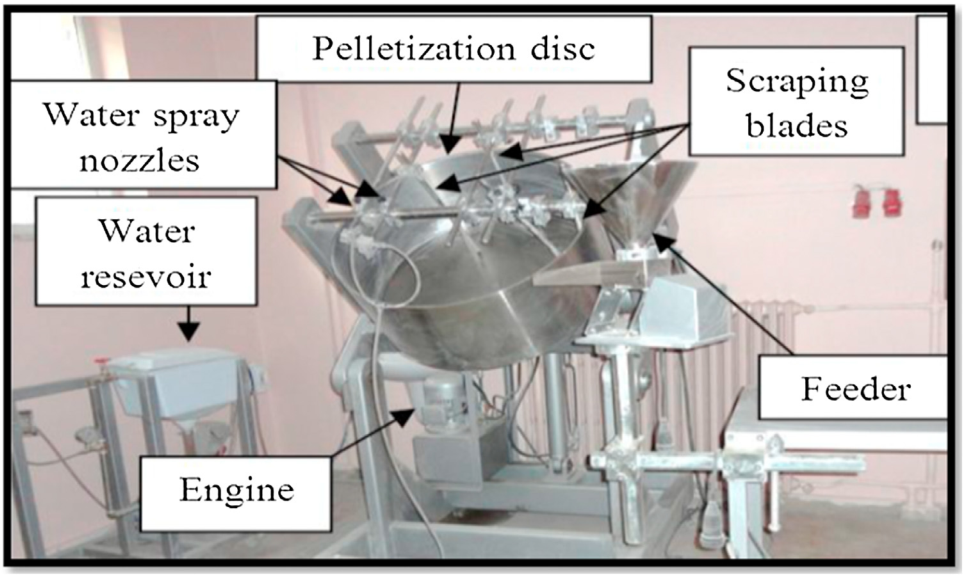

Fig. 1. The pelletized disk.

Fig. 2. Fresh particles of AFA in final state before curing in plastic bags.

Table 2
Sieve size and physical characteristics of NA and AFA.

Type of aggregate	Single sized aggregate (*mm*)	Aggregate nominal diameter (*mm*)	Specific gravity	Water absorption (%)
NA[a]	8.0–12.5	10.25	2.72	0.92
AFA[b]	8.0–12.5	10.25	1.78	17

[a] NA: Natural aggregate.
[b] AFA: Artificial cold bonded lightweight Fly ash Aggregate.

After all, a uniformly graded and hardened AFA was produced (see Fig. 2) through cold bonding of fly ash and cement. This AFA was utilized in the manufacture of the pervious concrete in current study. The particles of AFA have a size that allow them to pass through 12.5-*mm* sieve and remain on 8-*mm* sieve. The Physical characteristics of cold bonded AFA including: specific gravity (saturated surface dry condition) and water absorption [43] were 1.78 and 17 % by total weight for 24 h submerging, respectively. Sieve size and physical characteristics of both uniformly graded NA and cold bonding AFA are presented in Table 2. Besides the photographic view of the uniformly graded NA and AFA are illustrated in Fig. 3.

2.2. Mix proportions and casting

The initial step of this study was to produce sufficient quantities of AFA to make 8 mixtures of previous concrete made with AFA and two mixes made with natural aggregates. Therefore, totally 10 sequences of pervious concrete were designed and produced at two different w/c ratios (0.27 and 0.32). The cement quantity for two series was 420 and 270 $kg/m^{3,}$

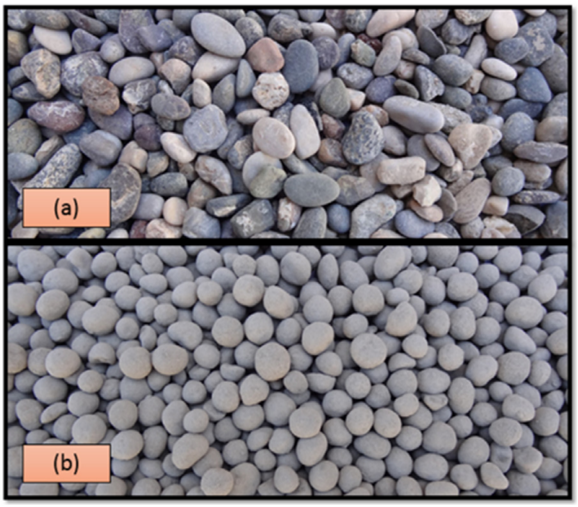

Fig. 3. Photographic view of uniformly graded a) NA and b) AFA.

Table 3
The Mix design of the study.

Mix Type	Mix ID	Cement (kg/m^3)	Water (kg/m^3)	Aggregate-to-cement ratio, (a/c)	NA (kg/m^3)	AFA (%)	AFA (kg/m^3)
0.27 w/c	27AFA0	420	113.4	3.70	1554.0	0	0.00
	27AFA25	420	113.4	3.38	1165.5	25	254.24
	27AFA50	420	113.4	3.06	777.0	50	508.48
	27AFA75	420	113.4	2.74	388.5	75	762.72
	27AFA100	420	113.4	2.42	0.0	100	1016.96
0.32 w/c	32AFA0	270	86.4	5.76	1554.0	0	0.00
	32AFA25	270	86.4	5.26	1165.5	25	254.24
	32AFA50	270	86.4	4.76	777.0	50	508.48
	32AFA75	270	86.4	4.26	388.5	75	762.72
	32AFA100	270	86.4	3.77	0.0	100	1016.96

respectively. The NA was substituted with cold bonding AFA with the volumetric substitution levels of 0–100% with a 25 % increment. Table 3 shows the details of the mix proportioning for the pervious concrete mixtures.

In Table 1, the code of the mixes starts with a number which refers to the w/c ratio of the mixtures, whereas the letters AFA and the following number represents the use of the percentage amount of used natural and artificial cold bonded fly ash aggregates and its content in the mixture. For instance, 27AFA25 represents that the pervious concrete mix is made with 0.27 w/c and includes 25 % of AFA and 75 % of natural aggregate. The water absorptions of NA and AFA were determined for 30 *min* since 30 *min* water absorption of the aggregates was about 95 % of 24-h water absorption. Both of the NA and AFA were submerged for 30 *min* in water before casting and getting saturated condition with surface dry. The used aggregates were dried with a towel so as to keep the water content of the mix. The material constituents that selected to produce the pervious concrete were mixed in a pan mixer with a capacity of 30 L and special mixing process for pervious concrete. Firstly, the aggregates were fed to the pan to blend for 30 s. After that, nearly 5% of Portland cement was added to the mixture with a little amount of water and the ingredients were mixed for 1 *min* to coat the particles of aggregates with a thick film of cement. Then, the remained quantity of cement and water were poured into the mixer for about 2 to 3 *min* to mix them properly. On the completion of the mixing process, the pervious concrete was placed into the moulds in 3 layer and each layer was compacted using a compaction rod. The produced concrete samples were kept at room temperature after being covered with wrapping plastic. After twenty-four hours, the produced samples were de-moulded and cured for twenty-seven days to be ready for testing.

2.3. Test specimens and methods

To perform the compressive strength test, cubic samples (150-*mm* dimensions) were used following the standard test of ASTM C39 [44] and for the permeability test, cylindrical specimens were used as per ASTM C496 [45]. The dry density and content of void were also carried out on the cylindrical specimen. The recorded results represent the average of the readings from three samples. The subsequent equation was utilized to measure the splitting tensile strength:

$$f_{splite} = \frac{2P}{\pi DL} \tag{1}$$

Where f_{split} is the splitting tensile strength in *MPa*, *P* is the ultimate load in *N*, *D* and *L* refer to the diameter and length of the cylinder-shaped sample in *mm*, correspondingly. The densities and content of void had been calculated as per ASTM C1754 [46] by the following equations:

$$Desnsity = \frac{K \times A}{D^2 \times L} \tag{2}$$

Where *K* is a constant and equal to 1,273,240 ($mm^3 kg/m^3 g$), *A* is the dry mass in gram, *D* and *L* are the diameter and length of the cylinder-shaped samples in *mm*, correspondingly. Then, the content of voids of the specimens was calculated by the following expression:

$$Content - of - void = \left[1 - \left(\frac{K \times (A - B)}{\rho_W \times D^2 \times L}\right)\right] \times 100 \tag{3}$$

Where *B* mass submerged in water in gram, ρ_w is the water density in kg/m^3. A falling head test apparatus confirming to the ASTM D2434 [47] which used to calculate the water permeability as shown in Fig. 4. The device is mainly utilized for measuring the permeability of cylinder-shaped specimens in which the sides of the specimens were covered by a layer of latex membrane firmly to prevent the leakage from edges, in this way water can flow vertically within the specimen (Fig. 4b). The cylinder-shaped specimens were set in a glass tube. For each of the specimens, four readings were recorded and the average these readings was considered as the final result. Consequently, by assuming a laminar flow, concerning Darcy's law

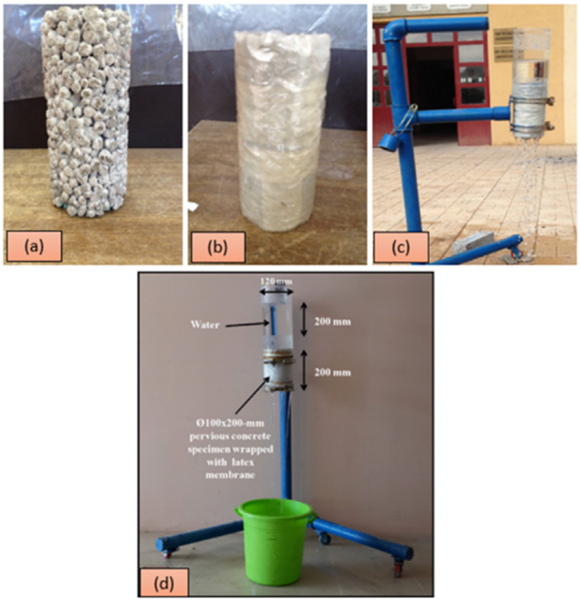

Fig. 4. Test of permeability: a) cylinder sample, b) sample prepared for testing, c) test device, and d) detailed test device.

was used to assess the coefficient of water permeability (k) in mm/s of the mixtures and the following formula was used:

$$k = \left(\frac{a \times L}{A \times t}\right) \ln\left(\frac{h_0}{h_1}\right) \tag{4}$$

Where a and A are the areas of cross-section area of the tube and the cross section area of the specimens in mm^2, correspondingly. L is representing the specimen length in mm, t is the elapsed time in Second, h_0, and h_1 are representing the initial water head (h_0) and the final water head (h_1) which were in mm, respectively.

The prismatic specimens with dimensions of $70 \times 70 \times 100$ mm were made to perform abrasion test. The Böhme abrasive wheel was utilized so as to calculate the resistance against abrasion of the samples as suggested in DIN52108 [48], with a steel disc of 750 mm in diameter and a revolving speed equal to forty cycles/minute. The lever arm of the test device also can perform three hundred N on the samples (Fig. 5). After weighting the prepared samples that were $70 \times 70 \times 100$ mm in dimensions, they were placed on the abrasion wheel surface with spreading twenty gram of wear dust of crystalline Al_2O_3 on

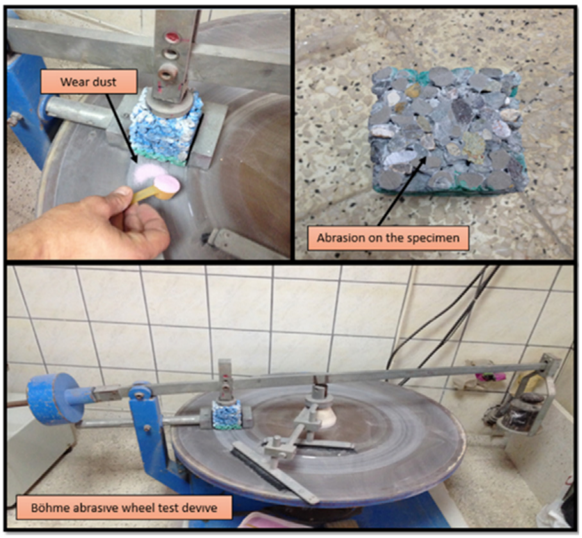

Fig. 5. Böhme abrasive wheel test device.

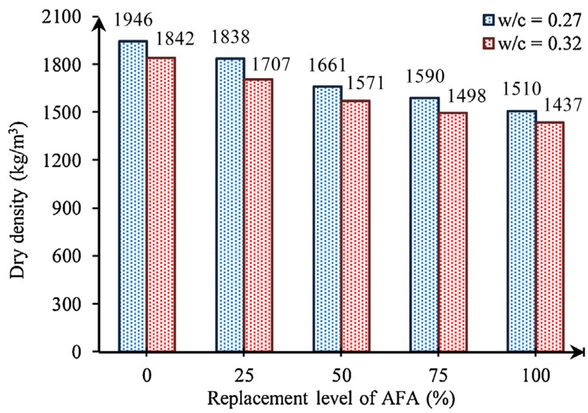

Fig. 6. Dry density of pervious concrete versus replacement level AFA.

the surface of the disc. The exposed face of the specimen to abrasion should be rotated four times with an angle of 90° without changing the selected face while for each period the disk was rotated to twenty two cycles. Then, the specimen's abrasion surface and abrasive wheel were cleaned. This procedure is usually called a spin and four spins were applied to each sample. After the 352 cycles, the prismatic specimen weighed and then the abrasion of the specimen by deep wear was measured in the following equation:

$$\Delta L = \frac{\Delta m}{\delta R \times A} \quad (5)$$

Where ΔL, Δm is the abrasive wear for sixteen cycles as the average loss in sample thickness (ΔL) in *cm*, is the loss in weight after sixteen cycles in gram, δR is the density of the sample in g/cm^3 and A is the area of this surface that selected for the abrasion in cm^2, correspondingly.

To determine the impact of the w/c ratio and AFA content on the engineering properties of the pervious concrete mixes, the outcomes were also evaluated by a statistical tool. Hence, the analysis of variance (ANOVA) was selected to designate the influence of independent variables on the dependent variable. For this purpose a software named Minitab were used [49].

3. Results and discussion

3.1. Dry density and content of void

Dry density values of the hardened pervious concrete via artificial cold bonded fly ash aggregate (AFA) content are presented in Fig. 6. Dry density values for 0.27 and 0.32 water-to-cement ratio (w/c) of control mixes were 1946 and 1842 kg/m^3, respectively, which is equal to 70–82 % of conventional concrete. However, when 100 % of AFA utilized, the density values were decreased to 1510 and 1437 kg/m^3 for the same aforementioned w/c ratios, correspondingly. As much as the AFA content increases the density decreases in a systematic way due to its very low specific gravity with high absorption of water.

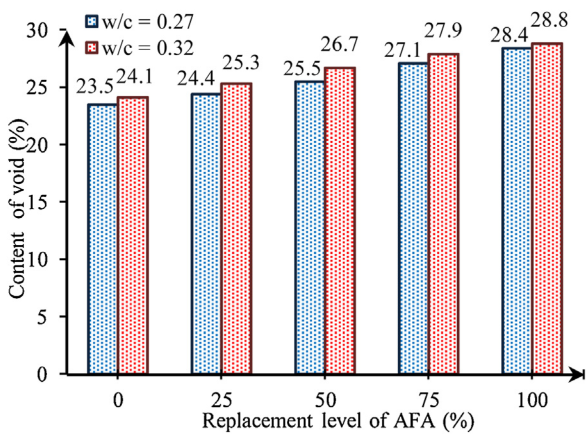

Fig. 7. Content of void of pervious concrete versus replacement level of AFA.

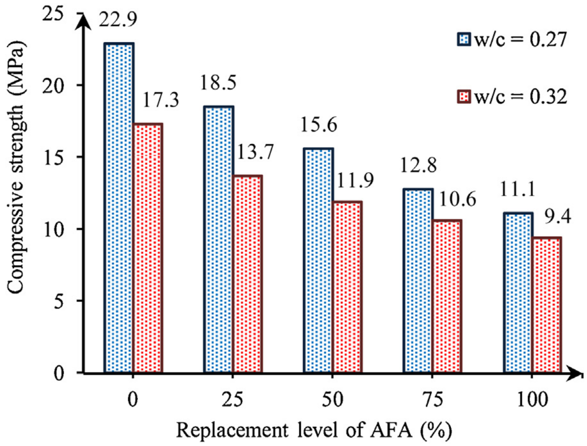

Fig. 8. Compressive strength of pervious concrete versus replacement level of AFA.

Besides, other factors that influenced the density of the produced pervious concrete are the cement content and w/c. In addition to that, the lower result of dry density was observed with high w/c. This could be clarified by the content of cement. Cement content used for the production of the 0.27 w/c of concrete samples were higher than that of 0.32 w/c, thus the voids between adjacent particles of the aggregate will be filled. Therefore, for the 0.27 w/c proportion heavier pervious concretes were achieved [37].

The content of voids in the samples of pervious concrete via replacement level of AFA are illustrated in Fig. 7. The spherical shape of the cold bonded AFA particles played a key role in increasing the presence of the voids in concrete mixtures. This can explain the increase in the voids content of the pervious concrete with the increase of the content of AFA. However, mixtures containing natural aggregates (NA) particles, which have irregular shape, showed lower voids content. This could be due to the better packing irregular NA particles than spherically shaped cold bonded AFA particles. Besides, it was realized the w/c has an effect on the content of voids in the specimens. The mixtures made with lower w/c ratio exhibited lower content of voids due to the increase in the thickness of paste covering the aggregates [50].

The content of voids increased from 23.5% to 28.4% and 24.1% to 28.8% when the substitution of NA with AFA increased from 0 to 100 for the 0.27 and 0.32 w/c, correspondingly. At w/c of 0.27, the voids content of the mix made with 100 % AFA increased by approximately 20.9 % compared to that of the mix incorporating NA, whereas, this increase was about 19.5 % at w/c of 0.32. An increase in the water/cement from 0.27 to 0.32 led to an increase in the void content by 2.6 % and 1.4 % for the specimens that including 100 % NA and AFA, correspondingly. The voids content results of the concrete mixtures in this experimental work meet the requirements of ACI522R-10 [16].

3.2. Compressive strength

The results of the compressive strength of the pervious concretes made with various replacement levels of NA with AFA are illustrated in Fig. 8. With regard to the effect of the content of AFA, it was observed that the strength of the pervious concrete decreased systematically as the content of AFA increased. This reduction in strength is due the fact that the AFA has lesser particle strength than NA. AS can be seen, the general trend is that the reference mixes exhibit higher compressive strength than those made with AFA and mixes made with lower w/c ratio show higher compressive strength. For example, the mix made with NA and w/c ratio of 0.27 had the highest compressive strength (22.9 *MPa)*. One possible way to enhance the pervious concrete's compressive strength is to upgrade the quality of the cement paste by reducing the water content of increasing the cement content [51]. Another way is that pervious concrete having lesser uniformly graded aggregate indicates a better compressive strength with a lower content of void due to increasing the surface area of aggregates [52].

The path of failure under compression load for the previous concrete mostly went within the cement matrix and the interfacial transition zone (ITZ) in the case of NA as shown in Fig. 9a. Additionally, replacing the natural aggregate with AFA created a different compressive failure path. More often the failure path propagates within the AFA particles as presented in Fig. 9b. The compressive strength of the pervious concretes ranging from 11.9 to 22.9 *MPa* and 9.4 to 17.3 *MPa* were achieved at the w/c of 0.27 and 0.32, correspondingly. It was reported that the pervious concrete with compressive strength values ranged between 3.5 to 28 *MPa* is acceptable for a wide range of applications [15,16]. The pervious concrete with a compressive strength of 13 *MPa* and a void content of 20 % could be used for parking lots [40]. Therefore, with using 50 % AFA content for 0.27 w/c in the production of pervious concrete a required strength and void content could be achieved.

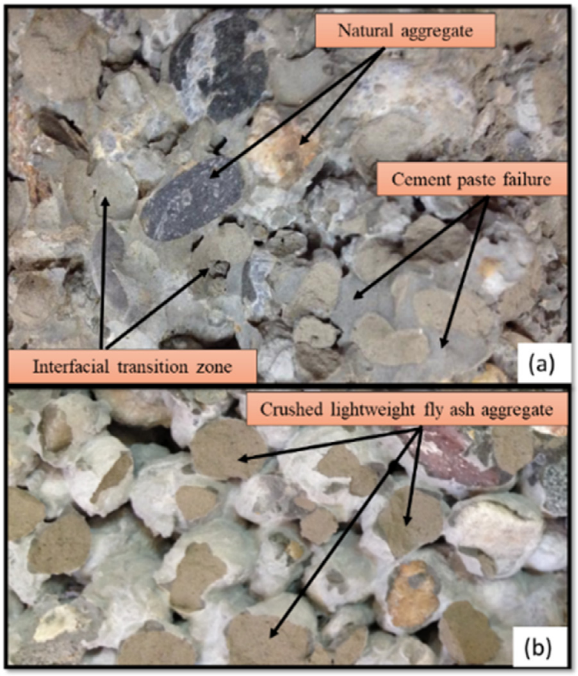

Fig. 9. Typical failure path in compressive strength test: a) through Cement matrix and interfacial transition zone (ITZ), and b) through AFA.

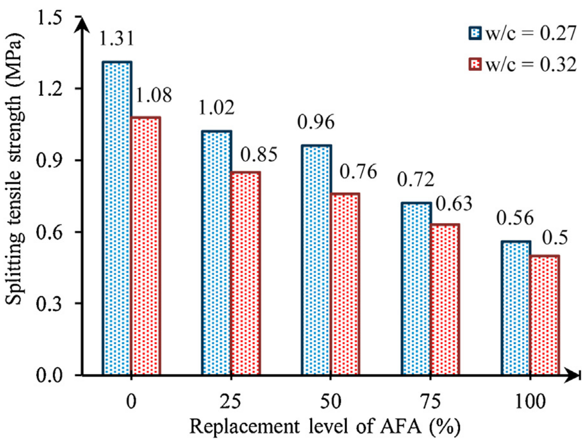

Fig. 10. Splitting tensile strength versus content of AFA.

3.3. Splitting tensile strength

The experimental outcomes of the splitting tensile strength test are presented in Fig. 10. The splitting failure path of the pervious concrete is unlike from compression failure path. The splitting failure path propagates through the cement matrix and both natural aggregate and cold bonded fly ash aggregates rather than the ITZ as shown Fig. 11. Whereas the failure path in compression generally passed through the cement matrix and/or the ITZ [37]. From the results a systematic reduction in pervious concrete tensile strength was examined by the increment in the replacement level of AFA content. Furthermore, a lower tensile strength of 0.5 *MPa* was achieved in this study in the case of the 0.32 of w/c. Therefore, the produced specimens at 0.27 w/c has more strength in the matrix of cement compared to that of made with w/c of 0.32, as the former has a thicker cement paste film covering the aggregate particles and the bond between aggregate particles becomes stronger [37]. In this study, the tensile strength test results were located between (0.5–1.31) *MPa*.

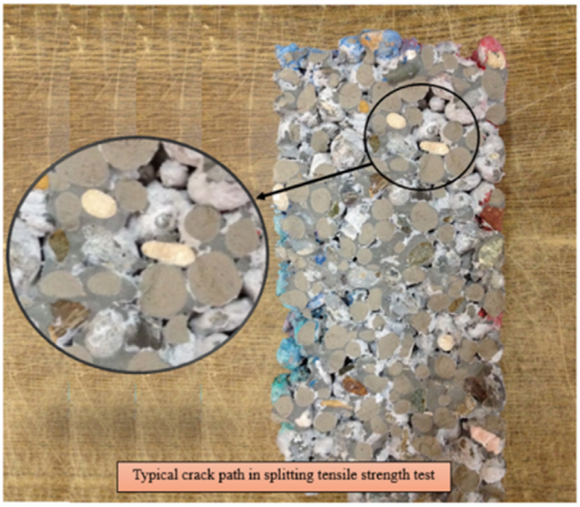

Fig. 11. Typical failure paths in splitting tensile strength test.

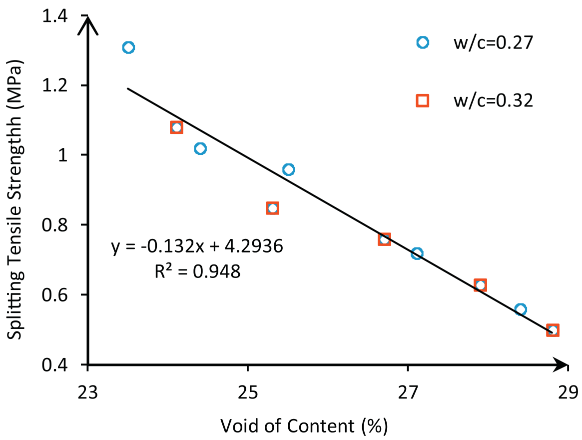

Fig. 12. Relationship between Splitting tensile strength and content of void of pervious concrete.

The correlation coefficient, R-square for the splitting tensile strength vs the content of voids was shown in Fig. 12. The 0.948 shows a very strong relationships between splitting tensile strength versus content of void. From the relationships conclude that splitting tensile strength decreased with increasing content of void.

3.4. Permeability

The most significant characteristic of the pervious concrete is its capability to percolate water within the voids. The permeability rate of such concrete straightly depends on the porosity and the pore sizes [19]. The permeability of pervious concrete vs the level of replacement of NA with AFA is demonstrated in Fig. 13. The coefficients of permeability of the pervious concretes were calculated by the head falling principle. The utilization of AFA in the pervious concrete increased the permeability coefficient because of its spherical shape that increased the pores and connectivity of the pores. Hence, the permeability of pervious concrete is directly proportioned to the content of AFA. Moreover, it was observed that with using a high aggregate-to-cement ratio (a/c) lead to high permeability coefficient. In this study, the concrete produced with 0.27 w/c had a lower a/c than that produced with 0.32 w/c, due to existing higher cement content in the former and the high amount of cement paste increased the cement paste thickness and filled the existing voids of adjacent aggregates. As a result, a lower value of permeability was obtained.

The permeability coefficient values for the pervious concrete made with NA were 6.01 and 7.82 *mm/s* for w/c ratios of 0.27 and 0.32, correspondingly. Moreover, when the AFA content increased up to 100 %, the permeability coefficient increased

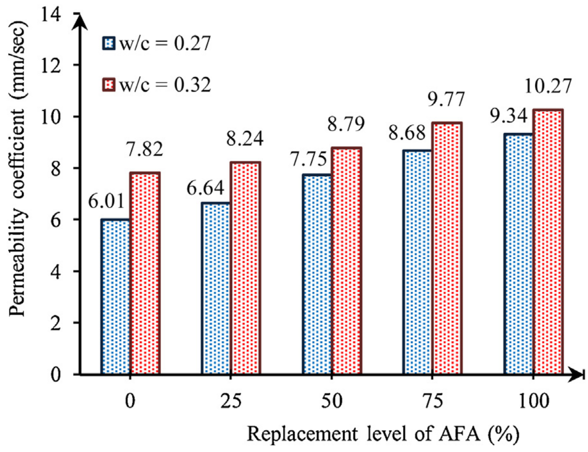

Fig. 13. Permeability of pervious concrete versus replacement level of AFA.

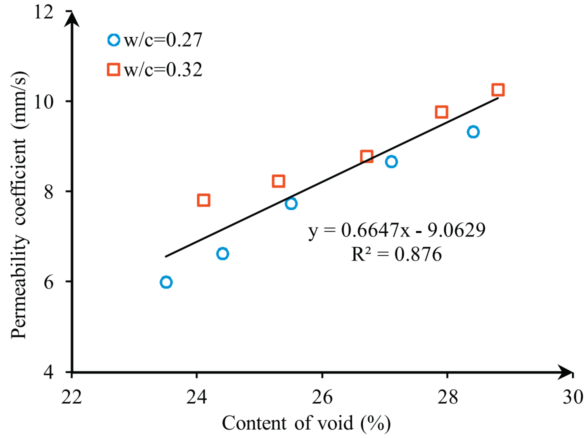

Fig. 14. Relationship between permeability coefficient and content of void of pervious concrete.

considerably to 9.34 and 10.27 *mm/s* and the increment rates of permeability were equal to 55.4 and 31.0 % compared to the aforementioned values of the two proportions of w/c, correspondingly. In General, the acceptable rate of permeability is usually in the range of (0.14–1.22) centimeter per second for permeable concretes [15,16]. In this experimental research work, the coefficients of permeability were acceptable and they could be classified as high permeability. From the previous studies, the content of void was increased by increasing the w/c due to the lower cement content. Also, increasing the AFA content that had the spherical particles could also increase the content of the voids. In this study, the increase of content of voids directly resulted in the increase in the permeability rate and this can be verified by the correlation for the permeability and content of voids as illustrated in Fig. 14. The value of R-square is 0.876 presented a good relationship for both permeability and voids content. The highest permeability of 10.27 *mm/s* achieved in the case when the voids content reaches the highest value of 28.8 %. Generally, the water permeability coefficient values ranged from 4.8 to 9.3 *mm/sec* is sufficient for using pervious concrete as a drainage layer for pavement structures [53].

3.5. Abrasion resistance

The AFA content and the water/cement ratio in this study affect the abrasion values as a means of durability properties of the pervious concrete. The depth of wear is used for testing prismatic specimens to find abrasion of the pervious concrete and results are presented in Fig. 15. The abrasion resistance of any pavement is the greatest significant characteristic related to all the surfaces as a cross point to the tire and base pressure directly [54]. The strength of the cold bonded AFA had a great effect on abrasion resistance of the pervious concrete. When the AFA content was increased, lower abrasion resistance was obtained. Hence, the best resistance to abrasion was observed in the control mixture at the w/c of 0.27; resulting from the enhancement in quality of the paste of cement and bond between particles of aggregate due to lower w/c. The abrasion

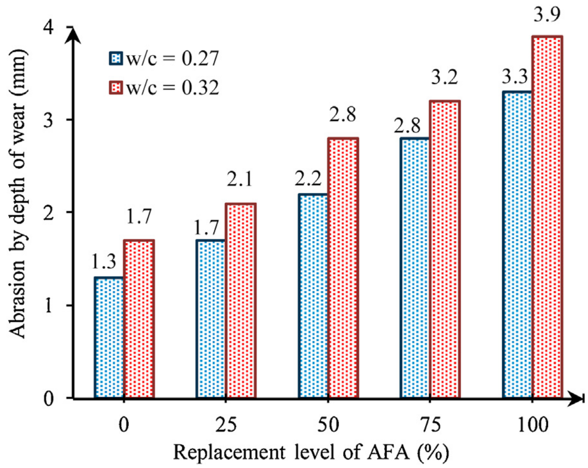

Fig. 15. Abrasion (by deep wear) of pervious concrete versus replacement level of AFA.

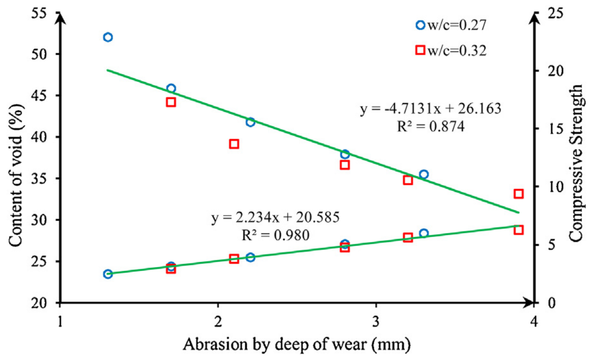

Fig. 16. Relationship between content of void-abrasion and compressive strength-abrasion of pervious concrete.

values of the mix control at the 0.27 and 0.32 w/c were 1.3 and 1.7 *mm* and they were increased up to 3.3 and 3.9 *mm* when 100 % of the natural aggregate substituted by AFA for the two w/c, respectively.

Moreover, the correlation for both content of voids and compressive strength vs abrasion resistance of the produced concrete are shown in Fig. 16. The values of R-square 0.874 and 0.980 demonstrated a strong relationship between the compressive strength-abrasion and content of voids-abrasion, correspondingly. Regarding the values of R-square, it may be concluded that increasing the content of void decreased the compressive strength as shown in Fig. 11, thus simultaneously decreased the abrasion resistance of the pervious concrete.

3.6. Statistical evaluation

Analysis Of Variance (ANOVA) was used to determine the effect of independent variables on dependent variables. The software named Minitab [49]. The general linear model ANOVA (GLM-ANOVA) is a vital analysis of statistics and investigative instrument that is usually utilized to measure the dominant factor by decreasing variance control. The process was carried out with significance level of 0.05 to determine statistically important variables that have the most effect on the characteristics of the pervious concrete. For this, the efficiency of the variables was evaluated using the GLM-ANOVA (Table 4). The values of P specify the effective variables on the characteristics of pervious concrete. If $P < 0.05$ then the parameter can be considered as a parameter with significant influence on the outcome. For the previous concrete, the dependent variables are the investigated properties such as (dry density, content of voids, etc.) while the w/c and the level of AFA defined as independent influence. Likewise, rate of contribution was utilized to determine the impact of each independent factor on the dependent variables such that the higher the contribution, the effectiveness of the factors to that particular response was higher, similarly, if the rate is low, the contribution of the influence on that specific response is fewer. Moreover, the contribution percentage of the *w/c* and AFA content were measured by dividing the sequential sum of squares rate of each independent variable to the total sequential sum of squares rate. The statistical evaluation indicated that both

Table 4
Statistical evaluation of the performance properties of the pervious concretes.

Dependent variable	Independent variable	Sequential sum of squares	Computed F	*P* value	Significance	Contribution (%)
Dry density	w/c	24,010	103.8	0.001	Yes	9.2
	AFA content	235,173	254.2	0.000	Yes	90.4
	Error	925	–	–	–	0.4
	Total	260,108	–	–	–	–
Content of void	w/c	1.521	33.1	0.005	Yes	4.8
	AFA content	30.076	163.5	0.000	Yes	94.6
	Error	0.184	–	–	–	0.6
	Total	31.781	–	–	–	–
Compressive strength	w/c	32.400	23.5	0.008	Yes	20.4
	AFA content	120.626	21.9	0.006	Yes	76.1
	Error	5.510	–	–	–	3.5
	Total	158.536	–	–	–	–
Splitting tensile strength	w/c	0.05625	21.4	0.010	Yes	9.6
	AFA content	0.51754	49.3	0.001	Yes	88.6
	Error	0.01050	–	–	–	1.8
	Total	0.58429	–	–	–	–
Permeability coefficient	w/c	4.1861	56.0	0.002	Yes	26.1
	AFA content	11.5491	38.6	0.002	Yes	72.0
	Error	0.2993	–	–	–	1.9
	Total	16.0345	–	–	–	–
Abrasion resistance	w/c	0.576	96.0	0.001	Yes	9.2
	AFA content	5.640	235.0	0.000	Yes	90.4
	Error	0.024	–	–	–	0.4
	Total	6.240	–	–	–	–

independent variables w/c and cold bonded AFA content had a remarkable influence on the all properties that conducted in this study referred to the P value as the P values are lower than the significance level of 0.05 as presented below. However, regarding the percent of contribution, it was observed that AFA content has a greater impact on the properties than the w/c with a high difference level. For instance, the compressive and splitting tensile strengths of pervious concretes that conducted in this study are significantly affected by the AFA content since their contribution percentage values are about 76.1 % and 88.6 %, whereas the contribution percentage for the w/c ratio is about 20.4 % and 9.4 %, respectively. Gaedicke et al., [55] stated that just the type of aggregate had a substantial influence on the compressive strength regarding to the porosity.

4. Conclusion

The following conclusions are drawn based on the experimental results of this study:

- Referring to ACI55R all density values of the pervious concrete were within allowable range. Dry densities have relatively decreased depending on replacement level of AFA because of its low specific gravity and high absorption of water. In the case of increasing AFA content from 0 to 100%, the decrease in dry density was about (22.4−22.0) % at 0.27 and 0.32 w/c, correspondingly.
- The spherical shaped AFA particles has increased the content of voids. By increasing cold bonded AFA content, the content of voids increases to a certain degree. At both w/c (0.27 and 0.32) the content of voids of pervious concrete were acceptable. Besides, the value of R-square 0.9555 indicated that the relationship of the dry density and content of voids in this study is very strong.
- A considerable decrease in the compressive strength is noticed depending on the replacement level of the AFA. The reduction in strength may be referred to the strength of the AFA particles. The results of compressive strength were acceptable at 0.27 and 0.32 w/c ratios, respectively. Besides, the pervious concrete with a lower w/c has developed greater compressive strength compared to the one with higher w/c.
- Splitting tensile strength of pervious concrete was decreased with increasing both w/c and AFA content. The values for the splitting tensile strength ranged between (0.5–1.31) *MPa*.
- The permeability coefficient was increased by raising the w/c from 0.27 towards 0.32 since the cement paste has decreased. Moreover, the use of more AFA as a replacement level was an effective way to improve the permeability of the pervious concrete which was the main objective of this study. Referring to ACI522R the pervious concrete is acceptable. Thus, the use of AFA in pervious concrete is thought to be very appropriate in capability to percolate the first-flush rainwater and to infiltrate it through the ground effectively.
- Adequate strength and void content of pervious concrete were achieved with using 50 % AFA content for 0.27 w/c that could be used for parking lots.

- Adding AFA as a replacement lowered the surface resistance for abrasion with reference to deep of wear. However, the decrease in the w/c has enhanced the abrasion resistance. With respect to the value of R-square, by increasing pervious concrete compressive strength higher resistance to the abrasion can be achieved.
- Both AFA content and w/c as an independent variable have a significant effect on the all properties of the pervious concrete conducted in this study when P value was regarded. By considering the percentage contribution values, it was cleared that AFA content was more effective on the pervious concrete properties than the w/c.

Declaration of Competing Interest

None.

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