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Influence of silica fume on the pervious concrete with different levels of recycled aggregates

***V.V. Galishnikova*[a]*, Sh. Abdo*[a*]*, A.M. Fawzy*[b]**
[a] Peoples' Friendship University of Russia (RUDN University), Moscow, Russia
[b] Alexandria University, Alexandria, Egypt
** E–mail: eng.shamseldin13@hotmail.com*

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Abstract. The world nowadays is trying to find alternative approaches to be used in manufacturing instead of consuming raw materials. Using recycled aggregates in new concrete is one of these effective approaches, which in turn reduces the quantity of waste and reduces the required landfills. In this present work, an attempt was made to study the effect of using recycled aggregates as an alternative to raw aggregates in pervious concrete with different levels (0 %, 25 %, 50 %, 75 % and 100 %), in addition to the impact of adding 5 % and 10 % of silica fume as a replacement of cement weight on the pervious recycled aggregate concrete properties. The concerned properties are as follows: fresh and hardened density, fresh and hardened voids content, water permeability, compressive strength, splitting tensile strength, flexural tensile strength, and potential resistance to degradation of the pervious concrete. Additionally, relations between water permeability and other parameters of the pervious concrete were deduced. Experimental results generally showed that by increasing the recycled aggregates' percentages, there was a consequent deterioration in concrete properties. Whereas, the addition of silica fume enhanced the mechanical properties. It was observed that the addition of 5 % silica fume to concrete with 50 % recycled aggregate was subsequently accompanied by 4.2 % and 5.5 % increase in the fresh and hardened pervious concrete density, respectively, while a 17.5 %, 11.7 % and 17.2 % decrease in the hardened concrete voids content, concrete permeability and concrete degradation, respectively. Regarding the strength parameters, the pervious concrete's 28 days compressive strength, 28 days splitting tensile strength and flexural tensile strength increased by 100 %, 20 % and 20.3 %, respectively, As follows, the addition of silica fume significantly improves the mechanical properties of the pervious concrete, with a slight decrease in the permeability parameters.

1. Introduction

Pervious concrete, also called porous concrete and permeable concrete, is a special type of concrete with high permeability that is used for concrete flatwork applications, which allows rainwater and other sources to penetrate through [1] (ACI 522.1-13). Presently, pervious concrete is mainly used in pavement, this attributes to its environmental advantages, such as reducing the rainwater runoff, maintaining the groundwater level, water pollution removal, reducing the need for retention ponds and other costly rainwater controlling, increases air and water ability to reach roots of trees, as well as it increases skid resistance and reduces friction noise [2–4]. Hence, due to all these benefits, many countries, especially in the United States, Japan and European countries, have been utilizing pervious concrete for over 30 years [5].

In order to obtain concrete with high permeability and high porosity, the fine aggregates should be excluded or minimized as possible, so that these distinctive properties could be achieved. Therefore, it is a mixture of Portland cement, water and one or two graded coarse aggregates with/out a small amount of fine aggregates. To maintain a low skeleton packing, one graded coarse aggregates are preferred, so that sufficient open pores could be formed in the matrix [6]. Convenient amounts of water and cementitious

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materials are used to create a paste, that covers the aggregates particles but leaves free spaces between them, hence pores are formed [6, 7], where it is recommended in ACI 522R to use a water/cement ratio varied from (0.26 to 0.4). However, in case of using low water/cement ratio, sometimes it is necessary to use chemical admixtures, such as water-reducing admixture, to reach the required concrete consistency and workability. Moreover, to ensure achieving the required workability, the hand ball rolling test should be conducted [8, 9].

As the world at the present tends to minimize the consumption of raw materials and energy, therefore, rather than making new products with virgin materials, they instead try to find alternative substances to produce the same products with reasonable quality. Thus, we can reduce the quantity of waste and save more landfills. As for concrete, extracting the coarse aggregates from the demolished concrete building wreckage, and reusing it in a new concrete is the new favorable trend, where it was found that in Europe more than 850 million tons per year of demolished construction wastes are generated, which accounts for 31 % of the total waste in Europe [10]. Hence, we could preserve the raw natural aggregates from consumption, where it is expected, in the USA, by 2020 that the need for producing aggregates would be more than 2.5 billion tons per year [11].

However, using the recycled aggregates in concrete causes adverse effects, where it is observed that by increasing the percentage of the recycled aggregates' proportion, there is a consequent reduction in the concrete mechanical properties. The occurred deterioration in the mechanical properties attributes to the higher water absorption, higher content of organic and harmful substances, lower density and the higher level of crushability compared with the properties of the raw aggregates. Additionally, the existence of old cement mortars on the recycled aggregates particles weakens the concrete and affects its mechanical properties, where it was found that in case of using recycled aggregates, there are two interfacial transition zones between the recycled aggregate and the concrete matrix: The first one is between the aggregate and the old cement paste, and the second one is between the recycled aggregate and the new cement paste [12, 13]. As a result, it was noticed that replacing the raw aggregates with recycled aggregates in the pervious concrete increases the voids ratio as well as decreases the compressive and tensile strength by more than 40 % [14, 15]. Hence, in some aspects using additives, such as silica fume, ground-granulated blast furnace slag, fly ash or chemical admixtures, is mandatory to partially compensate the consequent defects of the addition of the recycled aggregates [3, 16–22]. Additionally, a water compensation due to the high water absorption of the used recycled aggregates is required, where it is recommended to recognize the (10 min.) water absorption rate of recycled aggregates, since the concrete mixing procedures could be finished in 10 min and it accounts for 90 % of the absorbed water in the saturated state of the aggregates [15]. Additionally, some researchers suggested that the best replacement percentage of the raw coarse aggregate by the recycled ones is up to 30 % [23–26], even in some researches, the best replacement percentage is up to 60 % [12, 16], where there is no significant deterioration in the pervious concrete mechanical properties, meanwhile, some researchers found out that the mechanical properties of the pervious concrete are so sensitive, that the compressive strength is reduced even by about 10 % for every 10 % recycled aggregates replacement [19].

As foregoing, to overcome the deterioration occurred in the concrete properties due to the partial replacement of the raw aggregates with the recycled ones, there are several ways to enhance the concrete properties. One of those solutions is the use of pozzolanic material called silica fume. Silica fume is a by-product material which in turn leads to a reduction in waste materials. It is generated by the smelting process in the silicon and ferrosilicon industry as non-crystalline silica [27, 28]. It can be utilized in the form of densified powders or a slurry, as a combination at the concrete mixer, or even as a part of a factory-blended cement [29].

The partial replacement of cement with silica fume is chemically and physically beneficial. Physically beneficial due to the particle average diameter which is about 0.5 μm, thus the unreacted silica fume fills the micrometer-sized voids. Besides, its bulk density is about 600 kg/m^3, which is less than the bulk density of the cement which is 1440 kg/m^3, and hence the addition of silica fume will subsequently produce more gel than that produced by the cement, which means it densifies the concrete matrix. Additionally, using silica fume will reduce the consumption of cement, which in turn will reduce the emission of CO_2. For instance, it was found in Croatia that the Croatian cement industry causes around 8–9 % of total CO_2 emissions [30].

In terms of chemical reaction, since it is an amorphous material, it dissolves in the concrete before the reaction [31] and reacts with calcium hydroxide (C-H) in the hydrated cement, producing more gel, calcium-silicate-hydrate (C-S-H) [32]. Hence, silica fume decreases the concrete bleeding and produces a denser interfacial transition zone around the aggregates and the concrete paste, as well as a denser matrix, which in turn increases the strength parameters [33]. Besides, the size of the capillary pores and the crystalline hydration products are gradually decreased in the interfacial transition zone, as long as the pozzolanic reactions are ongoing. Thus, the transition zone thickness is reduced and the weak link in the concrete microstructure is minimized [34].

It is observed that the silica fume is a good replacement for cement. The optimum silica fume replacement percentage is about 10 % as a replacement for cement weight [21, 35, 36]. Therefore, in this research, a percentage of 10 % of silica fume was used as a maximum replacement percentage by cement weight. In return, there is an increase in the final cost of the concrete mixture, since the silica fume is more expensive than cement.

In this research work, the utilized recycled aggregates were extracted from concrete debris, which was collected from a demolished building with an age ranging from 40 to 50 years. The construction was in a dry environment during its lifetime. The debris was broken into pieces of about 9.5 mm size using a drilling machine and the Los Angeles machine. It was expected that no mineral or chemical admixtures were used in casting the old concrete, since in that time the concrete was just cast from conventional components.

Herein, the present research work was conducted to find out the impact of replacing 5 % and 10 % of cement weight by silica fume, on the one graded coarse aggregate pervious concrete with recycled aggregates. The replacement of recycled aggregates was at the levels of 0 %, 25 %, 50 %, 75 % and 100 % by the weight of the raw coarse aggregates. The properties of pervious concrete were concluded through permeability indices (water permeability, density and voids ratio) and strength indices (compressive, flexural tensile, splitting tensile strengths, in addition to the concrete potential to degradation). Additionally, relations between water permeability and other parameters of the pervious concrete were deduced.

2. Materials and Methods

2.1. Experimental program

Table 1. Concrete mixes' components.

Mix number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Silica fume (cement replacement ratio by weight)	0%					5%					10%				
Coarse aggregate replacement %	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
Water content (L/m^3)	105	108	109	111	113	105	108	109	111	113	105	108	109	111	113
Water/binder ratio	0.3														
Coarse aggregate content (kg/m^3)	1430														
Coarse aggregate nominal size (mm)	9.5														
Fine aggregate content (kg/m^3)	72														
Binder content (kg/m^3)	350														
High range water reducer (L/m^3)	2														

Table 1 shows 15 different mixtures' components for a 1 m^3 of concrete that have been used in this work. The mixes were designed according to (ACI-522R-10) with a 20 % designed porosity. Table 2 shows the quantity and dimensions of the specimens for each experiment of each mixture. In the results section, the plotted values were the average of the specimens' results for each experiment. In order to compensate the absorbed water by the recycled aggregate, an amount of water is added equal to the 10 min water absorption of the recycled aggregate.

2.2. Concrete components

In this research, all the components of the pervious recycled aggregate concrete -cement, water, aggregates and silica fume- passed the acceptance criteria experiments.

Portland cement Type I 42.5 N was used according to ASTM C150 [37], where its properties are presented in Table 3.

The coarse aggregates type, for both raw and recycled aggregate, was crushed pink limestone with single sizes of 9.5 mm. Its bulk density was 1760 kg/m^3 and the water absorption was 1.5 %. As for recycled coarse aggregate, the bulk density was 1630 kg/m^3, while the water absorption of recycled aggregate was 7.2 %.

Natural siliceous sand, with a bulk density of 1800 kg/m^3 and a fineness modulus of 2.67, was used as fine aggregate.

Micro silica (silica fume), with 92 % (SiO_2) content, 25000 m^2/kg surface area and 600 kg/m^3 bulk density, was used in this study to enhance the pervious concrete properties.

A poly-carboxylate based high range water reducer (HRWR) type F is utilized in this work with 1040 kg/m^3 bulk density.

Table 2. Quantity and dimensions of the specimens for each mixture.

Experiment type	Number of specimens	Shape and Dimensions

Fresh pervious concrete density and voids content	3	Cylinder D = 20 cm, H = 20 cm
Hardened pervious concrete density and voids content	3	Cylinder D = 7.5 cm, H = 15 cm
Water permeability test (falling head method)	3	50×50 cm^2 slab with a 10 cm thickness
Compressive strength	3	Cylinder D = 15 cm, H = 30 cm
Splitting Tensile strength	3	Cylinder D = 7.5 cm, H = 15 cm
Flexural tensile strength	3	15×15 cm^2 beam with a 45 cm span
Degradation and potential resistance	9	Cylinder D = 10 cm. H = 10 cm

Table 3. Properties of the used Portland cement.

Item	Percentage
Calcium oxide (CaO)	63%
Silicon dioxide (SiCh)	21.3%
Aluminum Oxide (Al_2O_3)	6.2%
Iron Oxide (Fe_2O_3)	3.9%
Magnesium oxide (MgO)	2.5%
Sulfur trioxide (SO_3)	1.7%
Potassium oxide (K_2O)	0.7%
Sodium oxide (Na_2O)	0.5%
Loss on ignition (LOI)	2.5%

2.3. Methods of testing

2.3.1. Fresh pervious concrete density and voids content

According to ASTM c 1688 [38], to obtain those properties, a sample of fresh pervious concrete is placed and well consolidated using the standard proctor hammer in a standard measure, then the density and the voids content can be calculated.

2.3.2. Hardened pervious concrete density and voids content

According to ASTM C1754 [39], hardened density and voids content are determined. Samples were dried at elevated temperature (105 °C), then the dried mass was recorded, then the specimens were submerged for 30 minutes to release the bubbles from the voids. Subsequently, the submerged mass for each specimen was recorded to determine the hardened density and the voids content. According to ACI 522R, the upper limit is 2000 kg/m^3 and the lower limit is 1600 kg/m^3 with voids ratio ranges from 15 % to 35 %.

2.3.3. Water permeability test (falling head method)

According to ASTM C1781 [40], the water permeability is expressed as infiltration rate, where a watertight infiltration ring with a 30 cm diameter is fixed on the surface of the concrete. The time that takes for the known mass of water to infiltrate through the ring is measured, the infiltration rate is calculated then. According to ACI 522R, the upper limit is 1.2 cm/s and the lower limit is 0.2 cm/s.

2.3.4. Compressive strength

According to ASTM C 39 [41], the ultimate compressive strength of a material is the value of the uniaxial compressive stress, when the material fails. According to ACI 522R, the compressive strength shouldn’t be less than 3 MPa.

2.3.5. Splitting Tensile strength

According to ASTM C496 [42], splitting tensile tests involve compressing a concrete cylinder on its side until a crack forms down the middle, causing the failure of the specimen. According to ACI 522R, the splitting tensile strength shouldn’t be less than 1 MPa.

2.3.6. Flexural tensile strength

According to ASTM C78 [43], the flexural strength test for concrete involves loading a 15x15 cm concrete beam with 45 cm span, the load is applied at one-third and two-thirds of the span length. According to ACI 522R, the flexural tensile strength shouldn’t be less than 1 MPa.

2.3.7. Degradation and potential resistance

According to ASTM C1747 [44]· this experiment is conducted to figure out the ability of the concrete to resist degradation from impact and abrasion. Cylindrical specimens of a known mass with a 10 cm diameter and a 10 cm height were inserted in the Los Angeles machine, three at a time, for 500 cycles without the steel balls. Thereafter, the crushed specimen is placed on a 2.54 cm sieve, the retained concrete on the sieve was weighed. The amount of material left behind was subtracted from the initial mass and the difference was taken as the mass loss percentage. According to ACI 522R, the upper limit is 95 %, while the lower limit is 19 %.

3. Results and Discussion

3.1. Density

The results of the density have standards deviation with a range of (10–25) kg/m^3. The following Figures 3.1.1 and 3.1.2 show the relation between concrete density (kg/m^3), recycled aggregate replacement percentage and the silica fume for the fresh and hardened pervious concrete, respectively. It's generally noticed that as a consequence of increasing the percentage of the recycled aggregates, there is an accompanying decrease in the fresh and hardened density. This decrease attributes to the lower density and higher voids ratio of the recycled aggregate itself, due to the aggregates' recycling process.

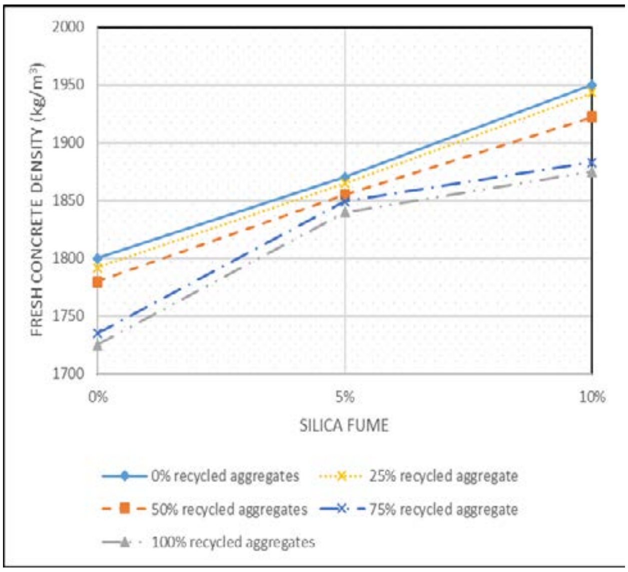

Figure 3.1.1. Density of the fresh pervious concrete.

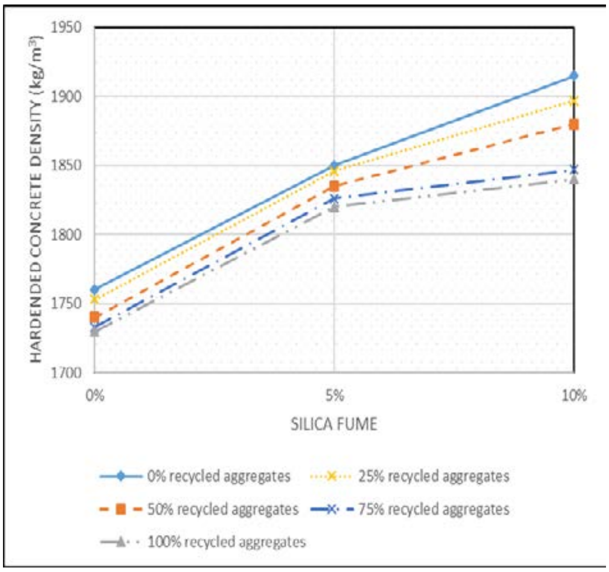

Figure 3.1.2. Density of the hardened pervious concrete.

3.2. Voids content

The results of the voids content have standards deviation with a range of (0.5–1.5) %. Figures 3.2.1 and 3.2.2 present the relation between the voids content and recycled aggregate replacement percentage along with the silica fume for the fresh and hardened pervious concrete, respectively. Generally, it is observed that by increasing the recycled aggregate percentage in the pervious concrete, there is a subsequent increase in the voids ratio for both the fresh and hardened concrete, which agrees with a previous scientific research [16], meanwhile contradicts with other [12]. As for voids content of the fresh pervious concrete, it's noticed that adding silica fume for the mixes with/out recycled aggregate greatly decreases the voids content, but since that the fresh state of the pervious concrete is in a short limited time, it could be overlooked. As for the voids content of the hardened pervious concrete, in case of 5 % silica fume, all the mixes with/out recycled aggregate are within the limits, whereas in case of 10 % silica fume, only the mixtures with 75 % and 100 % recycled aggregate meets the specifications, since the minimum voids ratio should be not less than 15 %, according to (ACI 522R-10).

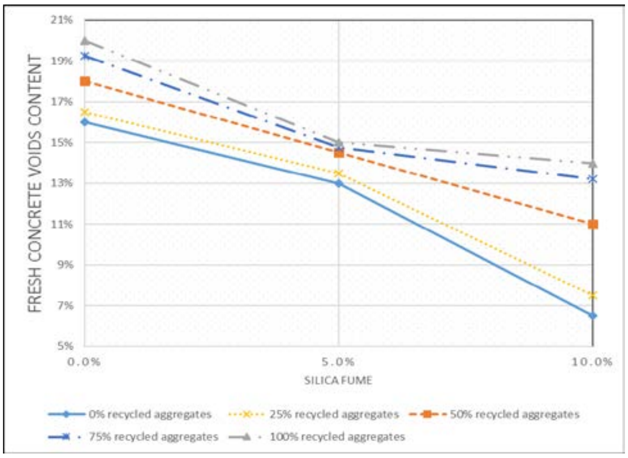

Figure 3.2.1. Voids content in the fresh pervious concrete.

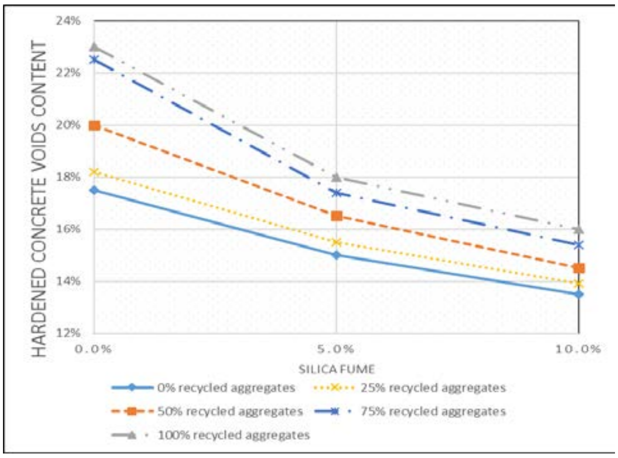

Figure 3.2.2. Voids content in the hardened pervious concrete.

3.3. Water permeability test (falling head method)

The results of the water permeability have standards deviation with a range of (0.02–0.04) cm/s. Figure 3.3 presents the relation between the water permeability and the recycled aggregate replacement percentage along with the silica fume for the hardened pervious concrete. It’s clearly noticed that silica fume decreases the water permeability. Whereas, increasing the recycled aggregate percentage increases the water permeability, where its is noticed that the addition of 5 % silica fume decreased the water permeability of the concrete by (13.5 %, 12.1 %, 11.7 %, 9.2 % and 7.8 %) for the concrete with (0 %, 25 %, 50 %, 75 % and 100 %), respectively, compared with concrete mixes without silica fume as shown in Figure 3.4.

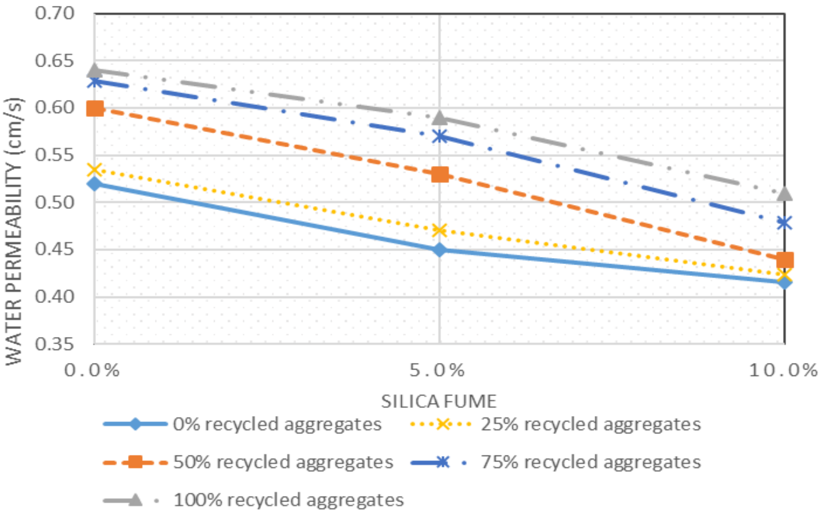

Figure 3.3. Water permeability of the hardened pervious concrete.

3.4. Summary of the effect of silica fume on the permeability parameters

The following Figure 3.4 shows the effect of silica fume on the permeability parameters of the recycled aggregate concrete permeability parameters. Mixes without silica fume are considered to be the control mix that all results are related to, for instance, mixes num. (6 and 11), (7 and 12), (8 and 13), (9 and 14) and (10 and 15) are compared with mix num. (1), (2), (3), (4) and (5), respectively. The Figure shows that adding silica fume subsequently increases the density of the fresh and hardened concrete, while decreases the voids content and the water permeability for both the fresh and hardened pervious concrete.

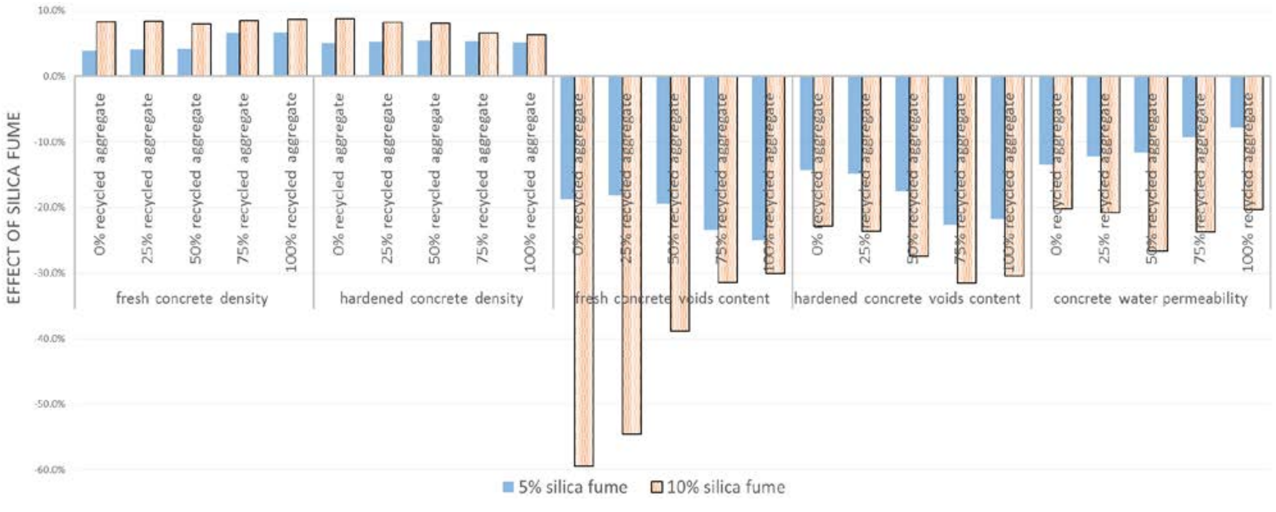

Figure 3.4. Effect of silica fume on the permeability parameters of the recycled aggregate pervious concrete.

3.5. Compressive strength

The results of the compressive strength have standards deviation with a range of (0.2–0.9) MPa. Figure 3.5 demonstrates the relation between 28 days concrete compressive strength (MPa), recycled aggregate replacement percentage and silica fume. It’s noticed that generally by increasing the percentage of the recycled aggregates, a consequent decrease in the compressive strength was accompanied as a result. However, the reduction due to the addition of up to 50 % of recycled aggregate could be neglected. As shown in the Figure 3.9. As a result of replacing 50 % of the raw aggregates with recycled ones, there is an accompanied reduction in the compressive strength by (8 %, 4 % and 7 %) for concrete with (0 %, 5 % and 10 %) of silica fume, respectively. This may be attributed to the weakness of the concrete in general, where there is plenty of voids in this type of concrete. Thus, the effect of the interfacial transition zone could be overlooked. Meanwhile, this contradicts with some researches [14, 26, 45], where they concluded that the best percentage for a replacing the raw coarse aggregate with recycled ones is up to 20 %. As for 100 % recycled aggregate, the amount and thickness of the interfacial transition zone between the aggregate particles and cement paste were considerably increased that the cracks propagate through it rather than through the cement mortar.

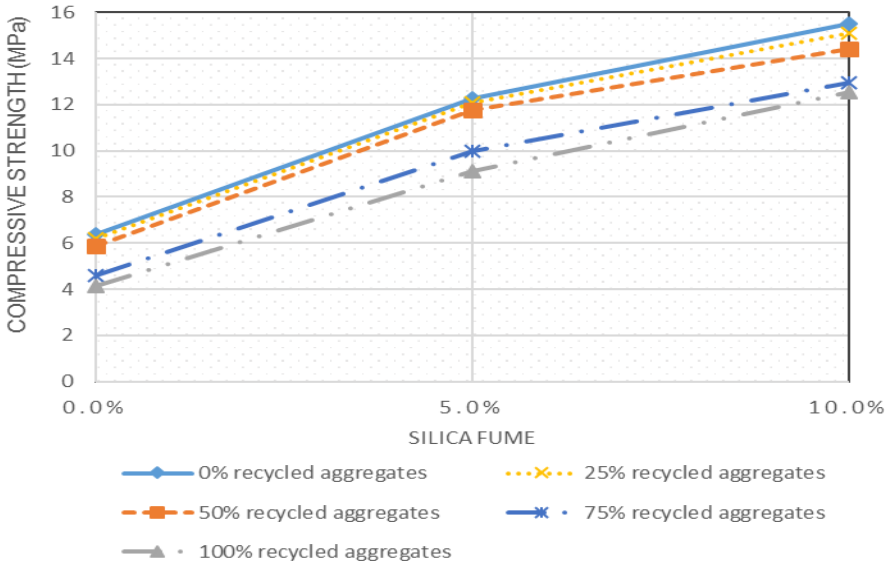

Figure 3.5. 28-day compressive strength of the pervious concrete.

Figure 3.9 emphasizes the explanation in the previous paragraph, where it is observed that the effect of silica fume is significantly increased for the 100 % recycled aggregate. It is noticed that adding 10 % of silica fume to the 100 % recycled aggregates, increased the compressive strength by 210 %. This is because silica fume enhances the concrete's matrix and the thickness of the interfacial transition zone in the concrete, as well as the degree of the orientation of the CH crystals in it [46].

3.6. Splitting tensile strength

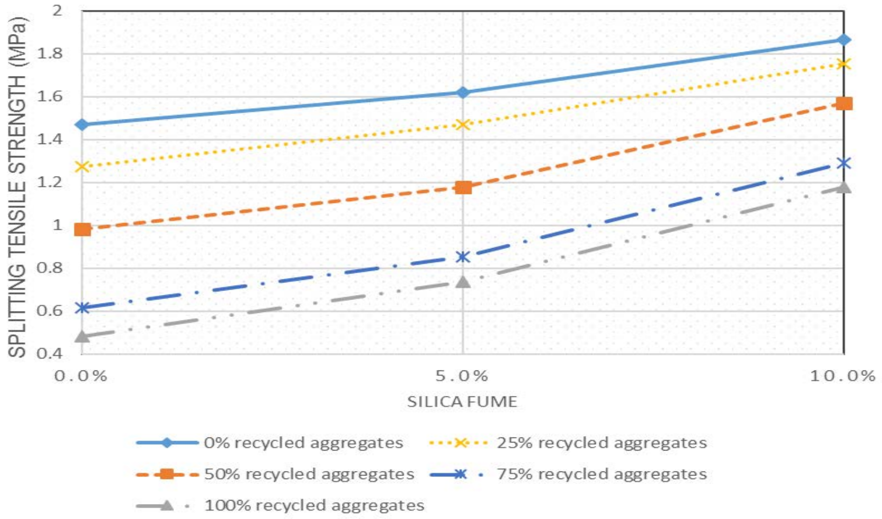

Figure 3.6. 28 days splitting tensile Strength of the pervious concrete.

The results of the splitting tensile strength have standards deviation with a range of (0.03–0.15) MPa. Figure 3.6 shows the relation between the 28 days pervious concrete splitting tensile strength (MPa) and the recycled aggregates replacement percentage in addition to silica fume. It is pronounced that the pervious concrete with 100 % recycled aggregate didn't meet the requirements and limits, that's in case of adding (0 % or 5 %) of silica fume.

It's also observed from the figure, that silica fume has a subsequent impact on the splitting tensile strength, especially when the percentage of the recycled aggregate increases. As shown in the Figure 3.9, the addition of 10 % silica fume for 100 % recycled aggregate pervious concrete, increases the splitting tensile strength by 148 %. This enhancement in the mechanical properties attributes to the improvements in the concrete matrix and the transition zone as a result of adding silica fume.

3.7. Flexural tensile strength

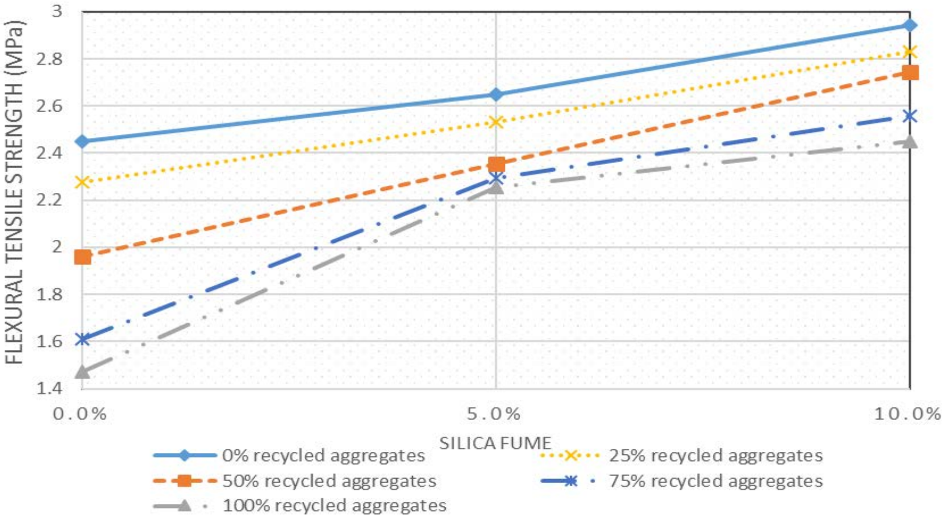

Figure 3.7. 28 days flexural tensile strength of the 28 days pervious concrete.

The results of the flexural tensile strength have standards deviation with a range of (0.08–0.27) MPa. Figure 3.7 shows the relation between the 28 days flexural tensile strength (MPa), the recycled aggregates replacement percentage and silica fume. It can be noticed that the flexural tensile strength is greater than the splitting tensile strength, since under bending stresses, just the member's extreme fibers are at the highest stress level, and if those fibers are defects free, the flexural strength will be controlled by the strength of those intact fibers. While if tensile stress is imposed on the concrete with the same properties, then all the fibers in the cross-section of the concrete are imposed on the same stress level and failure will initiate when the weakest fiber reaches its tensile strength.

3.8. Degradation and potential resistance

The results of the degradation and potential resistance have standards deviation with a range of (4–6.5) %. Figure 3.8 presents the influence of silica fume on the degradation of the pervious concrete with different percentage of recycled coarse aggregates. It is noticed from the figure that silica fume has a notable influence on the resistance to degradation of the concrete, where the degradation decreased by about 30 % when 10 % of the cement was replaced by silica fume as shown in Figure 3.9.

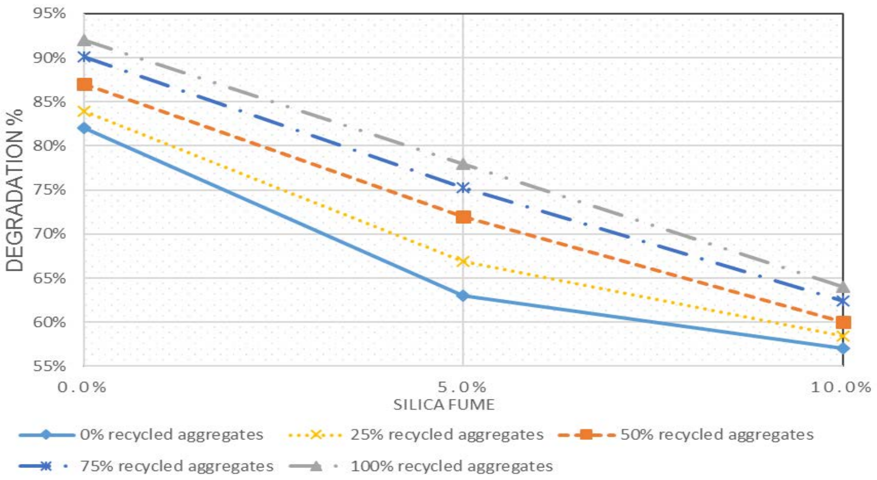

Figure 3.8. Degradation of the pervious recycled aggregate concrete.

3.9. Summary of the effect of silica fume on the strength parameters

Figure 3.9 shows the effect of silica fume on the strength parameters of the recycled aggregate concrete properties. Mixes without silica fume are considered to be the control mix that all results are related to, for instance, mixes num. (6 and 11), (7 and 12), (8 and 13), (9 and 14) and (10 and 15) are compared with mix num. (1), (2), (3), (4) and (5), respectively. From Figure 3.4 and 3.9, it is observed that replacing 10 % of cement with silica fume significantly enhance the properties, that in some cases it doesn't meet the ACI 522R limitations. Thus, replacing 5 % of cement weight by silica fume is an optimum replacement percentage. This agrees with some research works [47, 48]. From the Figure 3.9, it is observed that silica fume significantly enhanced the mechanical properties, for instance, it is shown that replacing 5 % of the cement by silica fume, doubled the compressive strength of the 50 % recycled aggregate pervious concrete. This enhancement attributes to the low density of silica fume compared with cement. Thus, replacing the cement with silica fume, results in larger paste volume, which in turn increases the strength of the bond between the matrix and the aggregate, which is the weakest phase in the pervious concrete.

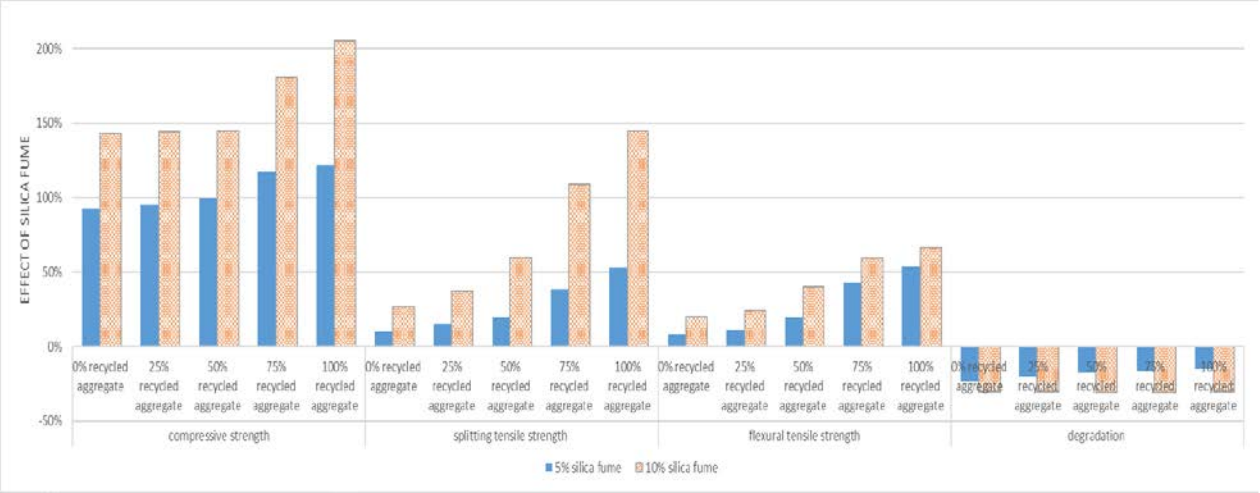

Figure 3.9. Effect of silica fume on the strength parameters of the recycled aggregate pervious concrete.

3.10. General relations between water permeability and other parameters

Since the water permeability is the ruling and critical parameter in pervious concrete, here in this part, an attempt was made to deduce correlations between the pervious concrete water permeability and other parameters.

Figure 3.10.1 presents the relationship between the water permeability in (cm/s) and the hardened concrete density in (kg/m^3). It can be noticed that by the increase of the concrete density (D), there is a consequent decrease in the water permeability (P). The deduced formula is with a good degree of fit (R^2 = 0.7513) and is as follows:

$$D = 1142.2P^2 - 1911.7P + 2497.7. \quad (1)$$

Figure 3.10.2 shows the relationship between the water permeability (P) in (cm/s) and the voids content percentage (V) of the hardened concrete. It is observed from the figure that there is a direct relationship between the voids content and the water permeability. The deduced formula is with a very good degree of fit (R^2 = 0.9309) and is as follows:

$$V = 1.1461P^2 - 0.8351P + 0.2898. \quad (2)$$

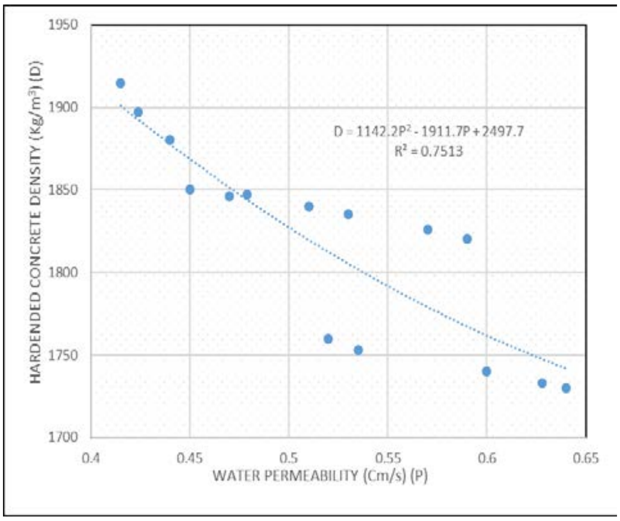

Figure 3.10.1. Correlation between water permeability and hardened concrete density.

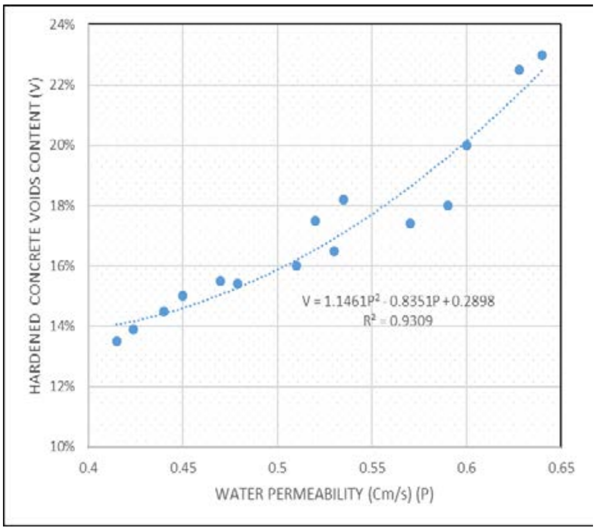

Figure 3.10.2. Correlation between water permeability and hardened concrete voids content.

Figure 3.10.3 shows the relationship between the water permeability in (cm/s) and the compressive strength in (MPa). It can be concluded that the relationship between the compressive strength (F_c) and the water permeability (P) is indirect. The deduced formula is with a good degree of fit (R^2 = 0.7805) and is as follows:

$$F_c = -46.651P + 34.454. \tag{3}$$

Figure 3.10.4 shows the relationship between the water permeability in (cm/s) and the tensile strength in (MPa), whether it is the splitting tensile strength (F_t) or the flexural tensile strength (F_b). Generally, it can be concluded that the relationship between the tensile strength and the water permeability (P) is indirect. The deduced formula between the water permeability and the splitting tensile strength is with a very good degree of fit (R^2 = 0.9208) and it is as presented in equation (4). Additionally, the formula between the water permeability and the flexural tensile strength is also with a very good degree of fit (R^2 = 0.9304) and it is as presented in equation (5).

$$F_t = -5.4468P + 4.0546; \tag{4}$$

$$F_b = -15.442P^2 + 10.89P + 0.9498. \tag{5}$$

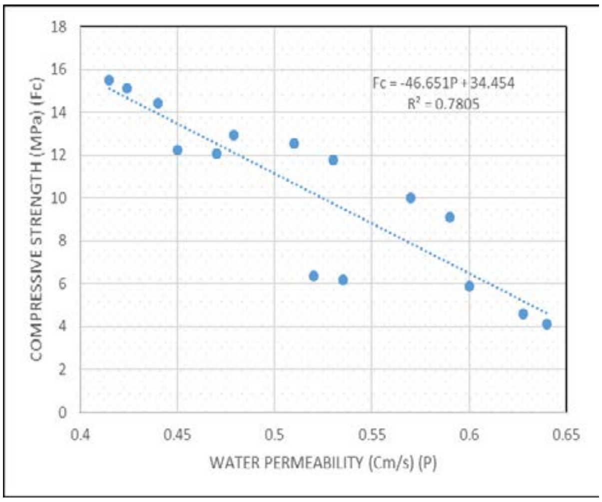

Figure 3.10.3. Correlation between water permeability and pervious concrete compressive strength.

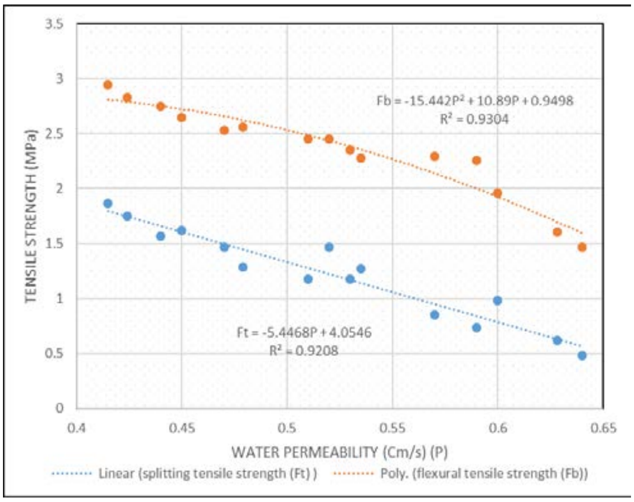

Figure 3.10.4. Correlation between water permeability and pervious concrete tensile strength.

Figure 3.10.5 shows the relationship between the water permeability in (cm/s) and the pervious concrete potential to degradation. It can be noticed that by the increase of the concrete water permeability (P), there is a consequent increase in concrete degradation (Deg). The formula which estimates this correlation is with a good degree of fit (R^2 = 0.8599) and it is as follows:

$$Deg = 1.4728P^{1.0818}. \tag{6}$$

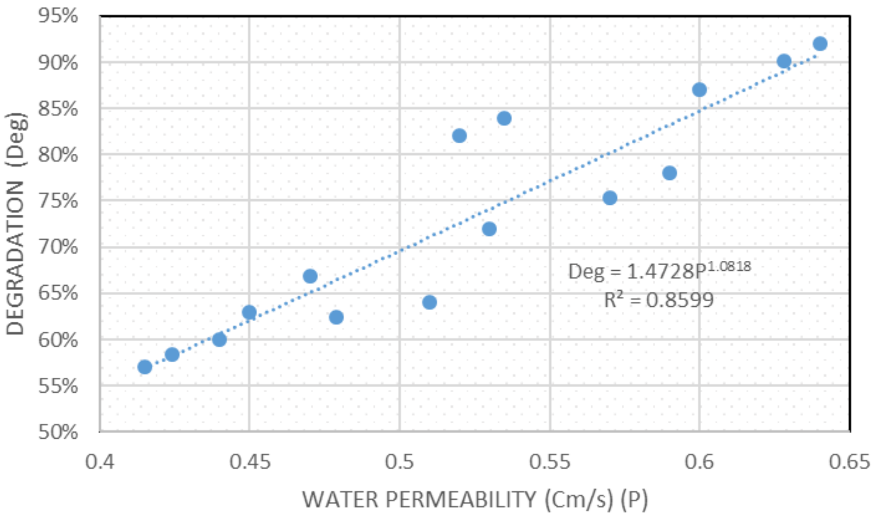

Figure 3.10.5. Correlation between water permeability and the pervious concrete degradation.

4. Conclusion

The study, in this research work, focused on the effect of replacing 5 % and 10 % of cement weight by silica fume on pervious concrete with recycled aggregates at the level of (0 %, 25 %, 50 %, 75 % and 100 %).

According to the previous findings, it is concluded that:

1. The replacement of raw aggregates with the recycled ones in the previous concrete adversely affects its mechanical properties. Meanwhile, this deterioration in the concrete properties could be neglected when up to 50 % of the raw aggregates are replaced, where the reduction in the mechanical properties is less than 10 %.

2. Generally, the addition of 10 % silica fume is not necessary, where it was found that adding 5 % silica fume is good enough to enhance the mechanical properties without affecting the permeability parameters. It was found that replacing 5 % of cement weight by silica fume in the pervious concrete with 50 % recycled aggregate, significantly increased the strength parameters and slightly decreased the permeability parameters, where the 28 days compressive strength, splitting tensile strength and the flexural tensile strength increased by 100 %, 20 % and 20.3 %, respectively. While the concrete potential to degradation, hardened density, hardened voids and water permeability decreased by 17.2 %, 5.5 % 17.5 % and 11.7 %, respectively.

3. In case of replacing 100 % of raw aggregates by recycled ones, the addition of 10 % silica fume is necessary in order to meet the specifications.

4. As a consequence of increasing the recycled aggregate replacement percentage, an increase in the used water is required, to compensate the water absorbed by the recycled aggregate.

5. By increasing the water permeability, there is a consequent increase in the voids content and the concrete potential to degradation, whereas a decrease in the concrete density, compressive and tensile strength.

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Contacts:

Vera Galishnikova, +7(915)379-24-68; galishnikova-vv@rudn.ru

Shamseldin Abdo, +7(999)519-37-18; eng.shamseldin13@hotmail.com

Ahmed Fawzy, +20(111)160-96-14; engahmedfawzy90@yahoo.com