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# Application of polymer, silica-fume and crushed rubber in the production of Pervious concrete

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**Abstract.** Achieving a pervious concrete (PC) with appropriate physical and mechanical properties used in pavement have been strongly investigated through the use of different materials specifically from the global waste materials of the populated areas. Discarded tires and the rubber tire particles have been currently manufactured as the recycled waste materials. In the current study, the combination of polymer, silica fume and rubber aggregates from rubber tire particles have been used to obtain an optimized PC resulting that the PC with silica fume, polymer and rubber aggregate replacement to mineral aggregate has greater compressive and flexural strength. The related flexural and compressive strength of the produced PC has been increased 31% and 18% compared to the mineral PC concrete, also, the impact resistance has been progressed 8% compared to the mineral aggregate PC and the permeability with Open Graded Fraction Course standard (OGFC). While the manufactured PC has significantly reduced the elasticity modulus of usual pervious concrete, the impact resistance has been remarkably improved.

**Keywords:** pervious concrete (PC); polymer; Silica fume (SF); rubber aggregate (RA); permeability; abrasion resistance; impact resistance

## 1. Introduction

Many researchers evaluate advances in concrete technology resulting from innovations to adapt the material for special engineering applications (Khanouki *et al.* 2016, Shariati *et al.* 2016, Toghroli *et al.* 2016, Khorramian *et al.* 2017, Toghroli *et al.* 2017, Hosseinpour *et al.* 2018, Paknahad *et al.* 2018, Shariat *et al.* 2018, Toghroli *et al.* 2018, Ziaei-Nia *et al.* 2018). The concrete is using in different aspects like considering PC as a sustainable pavement with high permeability, many studies have focused on producing a better physical and mechanical PC comprising density, strength, porosity, and permeability (Shen *et al.* 2013). Silica fume has been gained from the silicon metal, ferrosilicon alloys or the combustion of pulverized coal through the separators (mechanical & electrostatic) of the fuel gases from the power plants using coal as fuel. Considering the silica fume features (chemical & physical) within the concrete, it would be a very reactive pozzolan. While the silica fume has been applied to surpass the concrete's mechanical features and durability (Pelisser *et al.* 2011, Wang *et al.* 2012, Al-Tayeb *et al.* 2013, Vakili *et al.* 2013, Keyvanfar *et al.* 2014, Mohammadhassani *et al.* 2014a, Benaicha *et al.* 2015, Mohammadhassani *et al.* 2015, Padhi and Panda 2016, Safa *et al.* 2016a, Sata *et al.* 2016, Shahabi *et al.* 2016), a concrete with silica fume has held a high strength durable.

The application of different industrial mineral powders (silica fume & limestone filler) and organic products (super plasticizers & viscosity modifying agent) have significantly raised the range of concrete theoretical performance.

Regarding the waste tire management as a main environmental concern, majority of waste tires (over 50%) have been discarded with no reusing, thus innovative solutions have been developed by tire-rubber usage in asphalt or cement concretes (e.g., pavement materials) (Kim 2001, Wang *et al.* 2009, Paje *et al.* 2010, Moayedi *et al.* 2012, Güneyisi *et al.* 2014, Emiroglu *et al.* 2015, Chu *et al.* 2016, Toghroli *et al.* 2016) adding that the waste tire usage as concrete aggregates would be applicable with low cost (Abrham 2009). Majority of related studies have indicated that rubber aggregates have clearly improved the ductility, concrete hardness, and overcome the weakness of concrete brittleness (Sajedi 2012, Soltani *et al.* 2015, Farhan *et al.* 2016). Waste rubber tire as fine aggregates has been considered as low cost and sustainable option to river sand. Few studies have attempted to use waste rubber tire with

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low fine aggregate replacement as rubber ash.

Common properties like applicability, compressive and flexural strength, density, water absorption, abrasion resistance, carbonation depth, static modulus of elasticity, dynamic modulus of elasticity and chloride penetration of the concrete have been considered (Khatib and Bayomy 1999, Arabnejad Khanouki *et al.* 2010, Paje *et al.* 2010, Shariati *et al.* 2010, Hamidian *et al.* 2011, Pelisser *et al.* 2011, Shariati *et al.* 2011a, b, c, 1d, Sinaei *et al.* 2011, Muhammad *et al.* 2012, Shariati *et al.* 2012a, b, c, Sinaei *et al.* 2012, Mohammadhassani *et al.* 2013, Shariati 2013, Shen *et al.* 2013, Ashour and Kara 2014, Mohammadhassani *et al.* 2014a, b, Shariati 2014, Shariati *et al.* 2014a, b, Emiroglu *et al.* 2015, Khorramian *et al.* 2015, Shariati *et al.* 2015, Farhan *et al.* 2016, Safa *et al.* 2016a, Ji *et al.* 2017). Polymer pervious cement concrete has reduced the traffic noise and increased the pavement's drainage features (Gerharz 1999) on pavement friction course usage (Topcu 1995), therefore, a suitable ductility and toughness have been gained by a thin layer pavement friction course materials. Few tests have been applied to define silica fume activity in the concrete. The final strength has approximately indicated the content of active silica in the concrete volume. In the current study, the combination of polymer, silica fume and rubber aggregate produced from rubber tire particles have been used to obtain an optimized PC. Also, the scrap tire rubber aggregate has been applied to put the polymer PC mineral aggregate to develop the ductility and flexibility, then silica fume has been used to gain the most concrete strength (Pelisser *et al.* 2011) to prepare innovative polymer rubber aggregate PC.

## 2. Materials and methods

### *2.1 Materials*

In this paper, two types of fine aggregates including type A (1.18 to 4.75 mm) and type B (0.6 to 2.36 mm) were used (Fig. 1). The particle distribution curves have been shown (Fig. 2). When the rubber aggregate density is 1.02 g/cm$^3$, the cement is ordinary Portland cement (OPC) (Table 1) and styrene-butadiene latex is (milky fluid) SD623 (Table 2). A specific silica fume (Table 3) of spherical particles with less than 1 μm and averagely 0.15 μm have been applied. The bulk density has depended on the silo dense ratio with the range of 130 (non-densified) to 600 kg/m$^3$.

### *2.2 Concrete mix proportion*

Different types of concrete mix proportion have been defined as CSP, ASP and BASP (Table 4). When CSP is a polymer and silica fume PC with no rubber aggregates, ASP is a polymer and silica fume PC including diverse coarse aggregate volume replaced by type A (rubber aggregate), also BASP is a polymer and the silica fume PC that various fine aggregate volume has been replaced by type B. Considering seven replacement value ratio from 0% to 30%, i.e., 0%, 6%, 10%, 14%, 18%, 22%, 26% and 30% in ASP and BASP (Shen *et al.* 2013), the replacing value ratio of type A in BASP is 18% (Shen *et al.* 2013).

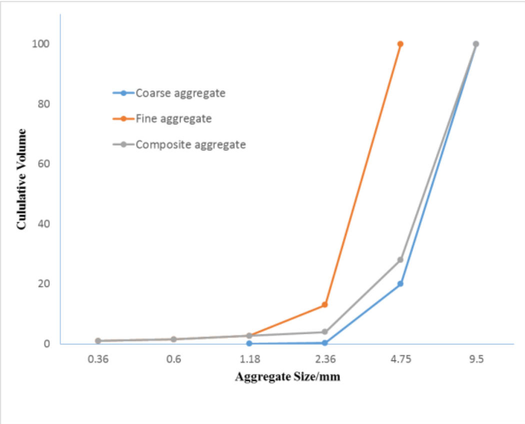



Fig. 1 Grain size distribution curves

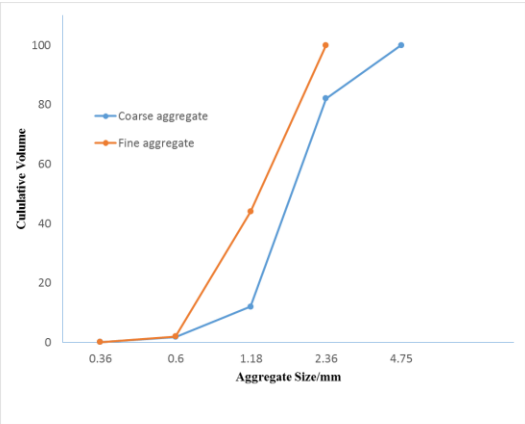



Fig. 2 Distributed particle size of rubber aggregate

Table 1 Physical and mechanical properties of OPC used in the research

| Physical properties | OPC |
|---|---|
| Apparent density (kg/m$^3$) | 3140 |
| Specific surface (m$^2$/kg) | 345 |
| Water demand of normal consistency (%) | 27.2 |
| **Setting time** | **(min)** |
| Initial | 130 |
| Final | 195 |
| Flexural strength (MPa) | |
| 3d | 6.9 |
| 28d | 9.4 |
| **Compressive strength** | **(MPa)** |
| 3d | 27.4 |
| 28d | 52.6 |
| Soundness | Qualified |

Table 2 Physical and mechanical properties of D623 (styrene-butadiene latex)

| **Physical properties** | **Value** |
|---|---|
| $SiO_2$ (%) | 90.90 |
| $Al_2O_3$ (%) | 1.12 |
| $Fe_2O_3$ (%) | 1.46 |
| CaO (%) | 0.69 |
| $SO_3$ (%) | 0.38 |
| Specific surface ($m^2$/kg) | 18000 |
| Density (kg/$m^3$) | 2260 |

Table 3 Physical and mechanical properties of silica fume used in the research

| **Physical properties** | **Value** |
|---|---|
| $SiO_2$ (%) | 90.90 |
| $Al_2O_3$ (%) | 1.12 |
| $Fe_2O_3$ (%) | 1.46 |
| CaO (%) | 0.69 |
| $SO_3$ (%) | 0.38 |
| Specific surface ($m^2$/kg) | 18000 |
| Density (kg/$m^3$) | 2260 |

Table 4 The mix proportions of polymer and rubber aggregate

| **Specimens** | **CSP** | **ASP** | **BASP** |
|---|---|---|---|
| Cement | 300 | 300 | 300 |
| Water | 48 | 48 | 48 |
| Coarse aggregate | 1800 | 1260-1800 | 1476 |
| Fine aggregate | 200 | 200 | 140-200 |
| Silica fume | 42 | 42 | 42 |
| Latex (water) | 54 (48) | 54 (48) | 54 (48) |
| **Replacing ratio of rubber aggregate by volume (%)** | | | |
| A | – | 0–30 | 18 |
| B | – | 0 | 0–30 |

The finer rubber aggregate has been applied to substitute the mineral aggregate avoiding the segregation to obtain matrix of equal void range on rubber aggregate with no matrix. According to the test results (not defined in this paper), in this material, the solid polymer is 19% (the latex is 18%) of cement mass and the silica fume is 14%. When the only gravity of silica fume has generally varied (2.2 to 2.3), the unique surface area of silica fume has varied from 15,000 to 30,000 $m^2$/kg.

### *2.3 Methodology*

#### *2.3.1 Strengths*

Three prism specimens as 40×40×160 mm were used to test the PC strength (Shen *et al.* 2013) with various value replacement of rubber aggregate in mineral aggregate have been gained (Table 4). The strengths have measured the effects of the rubber aggregate replacing rate on the polymer and silica fume strength.

#### *2.3.2 Stress - strain curves*

The prism specimens as 40×40×160 mm mixed with CSP, ASP-18 (type A & replacing value 18%), and BASP-14 (type B & replacing value 14%-18%) have been used to analyze the stress- strain behaviors to check the rubber aggregates' effects on the polymer and silica fume behaviors.

#### *2.3.3 Abrasion resistance*

The prism specimens as 40×40×160 mm of CSP, ASP-18 and BASP-14 have been used to measure their abrasion resistances analyzed with a wear loss per unit area computed by Eq. (1)

$$G = (m_1 - m_2) / S \tag{1}$$

In Eq. (1), the parameters are defined: G as the wearing loss per unit area (kg/$m^2$), $m_1$ as specimen origin amount, $m_2$ as the specimen amount after wearing (kg) and S as the wearing area ($m^2$).

#### *2.3.4 Impact resistance*

The specimens ϕ150 mm×64 mm of CSP, ASP18 and BASP-14 have been used to test the impact resistances in ACI-544 standard (Drop Weight method) resulting that the specimens have been impacted by a 4.5 kg steel ball dropping at 457 mm to be broken. Concrete toughness is

$$W = Nmgh \tag{2}$$

In Eq. (2), the parameters are defined: W as impact resistance in kN.m, N as impact times to break the specimen, m as the steel ball weight (4.5 kg), h as the ball drop height from (457 mm) and g as the gravitational acceleration (9.8 m/$s^2$).

#### *2.3.5 The porosity and permeability*

The concrete strength has been influenced by the overall voids' volume (Mui *et al.* 2010). Considering the complex concrete micro-structure, the pores has been presented from the nanoscale to the macro scale. Testing the $P_C$ porosity accurateness has been derived from its unique micro-structure. Comparing the pores of the cement paste, the connected voids between the coarse aggregate are few millimeters bigger. Regardless of the effective Mercury Intrusion Porosimetry (MIP) method to observe the pore configuration in normal concrete, the great quantity of integrated voids of PC have caused dripping and mercury leakage on pressure usage to make the method infeasible for PC. Practically, in case of setting up delicate tools to test an accurate porosity of PC in laboratory research, The vacuum sealing is adequately proper tools to fulfill this purpose (Huang *et al.* 2010). Kearsley and Wainwright have applied the Hoff equation (Hoff 1972) to claim the foam concrete's total porosity (Kearsley and Wainwright 2002). Zheng has also provided an equation to claim the PC total porosity as analogous to the Hoff equation, however, has incorporated the aggregate proportions for PC (Zheng *et al.* 2007) (Eq. 3).

$$\rho_t = \left( \frac{100 + P_c + 0.25P_c}{\frac{100}{\rho} + \frac{P_c}{\rho_c} + (0.25P_c \times 0.75)} \right) \times \rho_w \quad (3)$$

as theoretical density
$P_c$ as the cement aggregate level by weight
$\rho_c$ as the cement specific gravity
$\rho_w$ as the water unit weight
$\rho$ as the apparent density aggregate

The Eq. (3) has been derived by computing the cement hydration water to the cement by weight, thus the no-evaporable water mass (0.25) times the anhydrous cement mass $P_c$ and the volume of the water has been reduced to 0.75 of the original volume after chemically hydrating (Lian *et al.* 2011) (Eqs. 4 and 5)

$$n_o = \left( 1 - \frac{\rho_s}{\rho_t} \right) \times 100 \quad (4)$$

$$n_e = \left( 1 - \frac{m_2 - m_1}{v.\rho_w} \right) \times 100 \quad (5)$$

$n_o$ as PC theoretical porosity
$n_e$ as PC effective porosity
$\rho_s$ as concrete bulk density
$\rho_t$ as concrete theoretical density
$m_1$ as immersed specimen weight in the water after 24 h
$m_2$ as specimen weight after immersion and dried at 60℃ for 24 h
$v$ as the specimen volume
$\rho_w$ as water density.
The concrete permeability coefficient has been computed through Darcy Law (Eq. (6)) (Fig. 3).

$$K_T = \left( \frac{Q.L}{A.\Delta.t} \right) \quad (6)$$

$K_T$ as permeability coefficient at water temperature T ℃ (cm/s)
Q as permeating water quantity ($cm^3$)
L as measuring points' vertical distance in piezo-metric tubes (cm)
Δh as meaning head pressure (cm)
*t* as permeating time (s)
A as specimen cross area ($cm^2$)

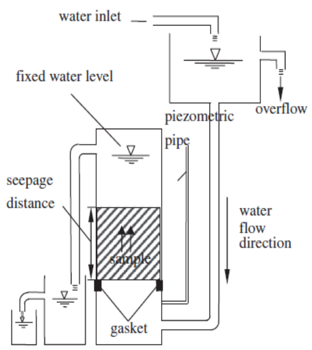
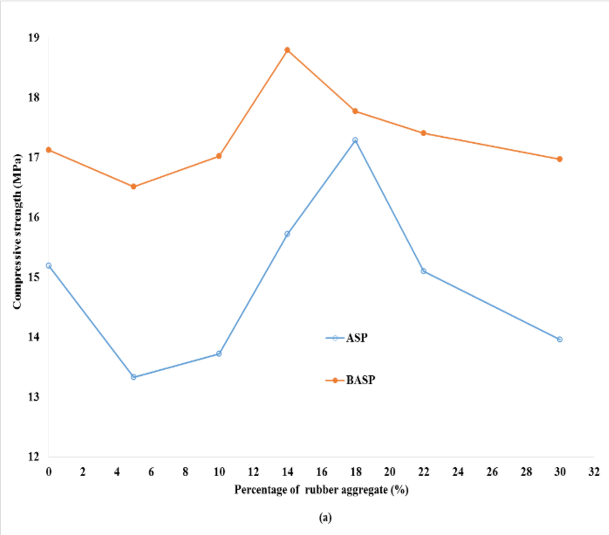



Fig. 3 Set up for measuring of concrete' permeability

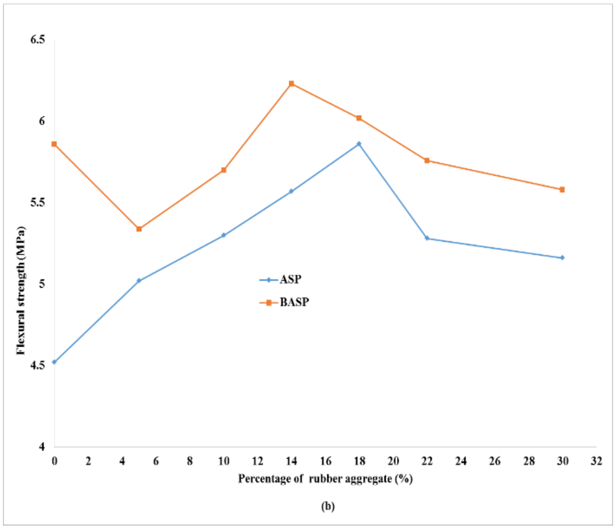
## 3. Discussion

### 3.1 Strengths

The flexural and compressive strength curves of different polymer and silica fume rubber aggregates PC with different rubber aggregates replacement range have been shown in Figs. 4(a) and 4(b). On increment of value replacement, the PC compressive and the flexural strength have primarily been reduced but have secondly raised to the highest values; flowingly, the compressive and flexural strength have been declined as well as representing a rubber aggregate replacing volume ratio to the mineral in the polymer and silica fume PC in ASP and BASP. On the lower replacement value to the optimum level, the rubber aggregates have not maintained a steady concrete, therefore, the concrete strength has been reduced due to some weak points of the rubber aggregates with low elasticity modulus making a stress concentration around the rubber particles (Mindess *et al.* 2003). Obtaining an adequate rubber aggregate content to distribute evenly through the material matrix, the load energy might be steady absorbed (Benazzouk *et al.* 2003) providing the increment of the concrete strength. When the replacement ratio has gained more optimum value, the soft rubber aggregates have weaken the PC frame-work led to the concrete strength reduction. While the optimum replacement value of type A is 18%, type B is 14% (Fig. 4). Comparing CSP-0 (polymer and silica fume PC with no rubber aggregate) to ASP-18 (polymer and silica fume rubber aggregate PC with rubber aggregate), the flexural strength of ASP-18 has been increased to 31%, when its compressive strength has raised to 18%. According to the literature, due to the adding rubber aggregate, the strength of compacting concrete has been reduced (Topcu 1995, Toutanji 1996, Alvarez *et al.* 2011, Pelisser *et al.* 2011), however, the flexural and compressive strength have been raised in case of rubber aggregate addition (Shen *et al.* 2013). Moreover, based on the current study's finding, adding the silica fume to the modified rubber aggregate PC has raised the flexural and compressive strength more than rubber aggregate PC without silica fume. The flexural strength increment ratio is 1%,
when the compressive strength ratio is 6% more than the modified concrete without silica fume. Therefore, the pavement materials' flexural strengths have related to the pavement performance than its compressive strengths indicating that the performance of PC (as a pavement friction course) has been developed by rubber aggregates. BASP-14 has been obtained by the fine aggregate replacement in ASP-18 with type B. The flexural strength and compressive strength of BASP-14 have raised to 6% and 8% compared to ASP-18. The small sized type B with silica fume have filled the gaps among the coarse aggregates distributed in PC much more uneven than type A, so the strengths of this series has been increased compared to ASP-18.




(a) Compressive strength




(b) Flexural strength

Fig. 4 The concrete strength

### *3.2 Concrete load-strain curves*

On the loading rate (0 - 500 N/s), the PC with a part of aggregates substitute by rubber aggregates i.e., ASP-18, BASP-14 have larger strain than CSP in the absence of rubber aggregates (Fig. 5). The ultimate stress and strain have been visibly developed showing that rubber aggregates have reduced the concrete elasticity modulus and improved the ductility. Therefore, the substitution of type B with rubber aggregate, the concrete's ultimate stress and strain have been improved.

Logarithmic Mixture Rule (three-phase elasticity composite modulus) have presented in Eqs. (7) and (8) (Mindess *et al.* 2003)

$$Log\, E_c = V_p \log E_P + V_a \log E_a + V_r \log E_r \tag{7}$$

$$E_c = {E_p}^{V_p} {E_a}^{V_a} {E_r}^{V_r} \tag{8}$$

$E_c$ as concrete elastic modulus

$E_p$ and $V_p$ as elastic modulus and volume fraction of the paste

$E_a$ and $V_a$ as the elastic modulus and volume fraction of the aggregates

$E_r$ and $V_r$ as the elastic modulus and volume fraction of the rubber aggregates

$E_a$ as larger than $E_r$. in the absence of rubber aggregates

The elastic modulus of the material is as Eq. (9)

$$E_{c1} = E_P^{V_P} E_a^{V_a} \tag{9}$$

Rubber aggregates applying, the elastic modulus of the material is as Eq. (10)

$$E_{c2} = E_P^{V_P} E_a^{V'_a} E_r^{\prime V_r} \tag{10}$$

Due to the rubber aggregates replacement with the same volume, the following equation is:

$$V_a = V_a' + V_r'$$

That is,

$$E_{c1} = E_P^{V_P} E_a^{V'_a} E_r^{\prime V_r}$$

Based on the Eqs. (7) and (8), $E_a$ is larger than $E_r$ and $E_{c2}$ is lower than $E_{c1,}$ then the rubber aggregates have majorly reduced the CSP elasticity modulus.

### *3.3 Abrasion resistance*

The wearing loss per unit area of ASP-18 & BASP-14 has been declined by 13% and 25% compared to CSP (Table 5). Also, the concrete abrasion process (fracture process) has meant that the material surface has 1) crack formation cycle and 2) crack propagation that have been lately extended leading to the small fragments occurred overburden and scraped from the matrix (Zhang *et al.* 2002, Benazzouk *et al.* 2003).

Comparing the rubber aggregate's smaller elasticity modulus to the mineral aggregate, on the substitution of some mineral aggregates by some rubber aggregates, the rubber aggregates have absorbed the stress and reduced the stress concentration range at the tip of initial cracks, then effectively restrained the former concrete internal cracks. When cracks have been formatted, the steady distribution of rubber aggregates has obviously restrained the cracks developing, then the PC abrasion-resistance has been improved.

Table 5 The abrasion resistance results

| Specimen | CSP | ASP-18 | BASP-14 |
|---|---|---|---|
| Wear of unit area (kg m$^{-2}$) | 4.066 | 3.535 | 3.054 |

### 3.4 Impact resistance

From the Drop-Weight process, the specimens have been influenced by a 4.5 kg steel ball dropping as 457 mm (height) to be broken. The morphology of fracture section of ASP-18 is more complex and uneven than CSP, so few cracks on complete propagating in BASP-14 have been observed, because rubber aggregates in the PC have significantly absorbed the impact energy and relieved impact damages (Turatsinze *et al.* 2005, Hernández-Olivares *et al.* 2007). Therefore, the PC with mineral aggregate substitute by rubber aggregate has required lower energy to be broken in; meanwhile, the pavement materials with rubber aggregates haveindicated obvious ductility nature (Turatsinze *et al.* 2005). The impact resistances of both ASP-18 and BASP-14 have been remarkably improved compared to CSP and the impact resistance of BASP-14 has been obviously progressed than ASP-18 (Table 6).

### 3.5 The porosity and permeability

An ideal method for pavement concrete has laid in a coarse granular skeleton developing stone- on-stone contacts and high connected air voids (AV) content providing a great friction as well as permeability to the pavement surface. The stone-on-stone contact of the coarse aggregate fraction has been applied to make a mix resisted to a stable disintegration, when the fine aggregate fraction has filled the AV structure made by the coarse aggregate in a compacted mixture (Gerharz 1999).

Table 6 The impact resistance results

| Physical properties | CSP-0 | ASP-18 | BASP-14 |
|---|---|---|---|
| Times of initial cracking | 585 | 598 | 618 |
| Times of breaking down | 593 | 621 | 645 |
| Impact resistance (kN. m) | 11.95 | 12.52 | 13.18 |
| Physical properties | CSP-0 | ASP-18 | BASP-14 |

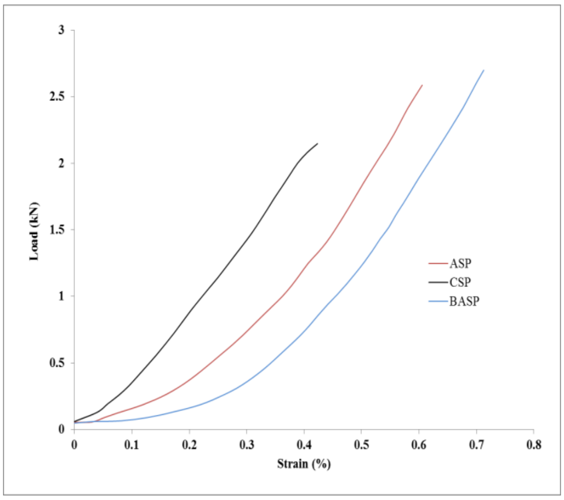



Fig. 5 Load- strain curves for concrete

Table 7 The impact resistance results

| Index | CSP | ASP-18 | BASP-14 |
|---|---|---|---|
| Effective porosity (%) | 18.8 | 18.0 | 18.4 |
| Whole porosity (%) | 19.9 | 18.6 | 19.5 |
| Permeability (cm/s) | 0.541 | 0.527 | 0.56 |

AV has provided drain ability and reduced the pavement's water damage showing that an air viscous flowing in the previous materials' microscopic channels has caused sound energy damping (Voronina 1997) providing sound falling on a thin surface pavement courses usage. Open-Graded Friction Course mix design (ASTM Designation: D7064/D7064 M – 08E1) has needed the OGFC porosity not less than 18% and a permeability more than 100 m/day (0.116 m/s). Therefore, the porosity of the mentioned concrete is more than OGFC (18%), also the permeability of the pavement wearing materials is more than 0.5 cm/s based on OGFC (Table 7).

## 4. Conclusions

According to the test results, the optimum replacement ratio of type A and type B are 18% and 14%, respectively; led to the highest flexural and compressive strength. However, the flexural strength has been clearly raised compared to the compressive strength of the mineral aggregate replaced with rubber aggregate. The PC elastic modulus have been reduced when the mineral aggregate has been substituted by rubber aggregate, then an increment has remarkably been occurred on the concrete ultimate stress and strain. Flowingly, the abrasion and impact resistance of the PC has been significantly developed by the mineral aggregate replaced by rubber aggregate and polymer, so the silica fume–rubber aggregate PC has shown ductility. The porosity of the friction course with more than 18% and the permeability with higher than 0.5 cm/s are above ASTM OGFC. Consequently, the PC has been applied as a friction course material for pavements. Interleaving of polymer film in the cement hydration products, the rubber aggregate distribution through the paste volume and the dense rubber cement paste interfacial transition zone have provided the polymer and silica fume–rubber aggregate PC ductility led to a greater function than the normal polymer PC as a pavement friction course material.

## References

Abrham, K.S. (2009), "the use of recycled rubber tires as a partial replacement for coarse aggregates in concrete construction".

Al-Tayeb, M.M., *et al.* (2013), "Experimental and numerical investigations of the influence of reducing cement by adding waste powder rubber on the impact behavior of concrete", *Comput. Concrete*, **11**(1), 63-73.

Alvarez, A.E., *et al.* (2011), "A review of mix design and evaluation research for permeable friction course mixtures", *Constr. Build. Mater*., **25**(3), 1159-1166.

Arabnejad Khanouki, M.M., *et al.* (2010), "Investigation of seismic behaviour of composite structures with concrete filled square steel tubular (CFSST) column by push-over and time-history analyses", *Proceedings of the 4th International Conference on Steel & Composite Structures*, 21 - 23 July, 2010, Sydney, Australia.

Ashour, A.F. and Kara, I.F. (2014), "Size effect on shear strength of FRP reinforced concrete beams", *Compos. Part B: Eng*., **60**, 612-620.

Benaicha, M., *et al.* (2015), "Influence of silica fume and viscosity modifying agent on the mechanical and rheological behavior of self compacting concrete", *Constr. Build. Mater*., **84**, 103-110.

Benazzouk, A., *et al.* (2003), "Effect of rubber aggregates on the physico-mechanical behaviour of cement–rubber composites-influence of the alveolar texture of rubber aggregates", *Cement Concrete Compos*., **25**(7), 711-720.

Chu T.H.V., *et al.* (2016), "Shear resistance behaviors of a newly puzzle shape of crestbond rib shear connector: An experimental study", *Steel Compos. Struct*., **21**(5), 1157-1182.

Emiroglu, M., *et al.* (2015), "A study on dynamic modulus of self-consolidating rubberized concrete", *Comput. Concrete*, **15**(5), 795-805.

Farhan, A.H., *et al.* (2016), "Effect of cementation level on performance of rubberized cement-stabilized aggregate mixtures", *Mater. Des*., **97**, 98-107.

Gerharz, B. (1999), "Pavements on the base of polymer-modified drainage concrete", *Colloids and Surfaces A: Physicochemical and engineering aspects*, **152**(1), 205-209.

Güneyisi, E., *et al.* (2014), "Experimental investigation on durability performance of rubberized concrete", *Adv. Concrete Constr*., **2**(3), 187-201.

Hamidian, M., *et al.* (2011), "Assessment of high strength and light weight aggregate concrete properties using ultrasonic pulse velocity technique", *Int. J. Phys. Sci*., **6**(22), 5261-5266.

Hernández-Olivares, F., *et al.* (2007), "Fatigue behaviour of recycled tyre rubber-filled concrete and its implications in the design of rigid pavements", *Constr. Build. Mater*., **21**(10), 1918-1927.

Hoff, G.C. (1972), "Porosity-strength considerations for cellular concrete", *Cement Concrete Res*., **2**(1), 91-100.

Hosseinpour, E., *et al.* (2018), "Direct shear behavior of concrete filled hollow steel tube shear connector for slim-floor steel beams", *Steel Compos. Struct*., **26**(4), 485-499.

Huang, B., *et al.* (2010), "Laboratory evaluation of permeability and strength of polymer-modified pervious concrete", *Constr. Build. Mater*., **24**(5), 818-823.

Ji, X., *et al.* (2017), "Anchorage properties at the interface between soil and roots with branches", *J. Forest. Res.*, **28**(1), 83-93.

Kearsley, E. and Wainwright, P. (2002), "The effect of porosity on the strength of foamed concrete", *Cement Concrete Res*., **32**(2), 233-239.

Keyvanfar, A., *et al.* (2014), "Application of a grounded group decision-making (GGDM) model: a case of micro-organism optimal inoculation method in biological self-healing concrete", *Desalination and Water Treatment*, **52**(19-21), 3594-3599.

Khanouki, M.M.A., *et al.* (2016), "Investigation of through beam connection to concrete filled circular steel tube (CFCST) column", *J. Constr. Steel Res.*, **121**, 144-162.

Khatib, Z.K. and Bayomy, F.M. (1999), "Rubberized Portland cement concrete", *J. Mater. Civil Eng*., **11**(3), 206-213.

Khorramian, K., *et al.* (2017), "Numerical analysis of tilted angle shear connectors in steel-concrete composite systems", *Steel Compos. Struct*., **23**(1), 67-85.

Khorramian, K., *et al.* (2015), "Behavior of tilted angle shear connectors", *PLoS ONE*, **10**(12), 1-11.

Kim, J.R. (2001), "Characteristics of crumb rubber modified (CRM) asphalt concrete", *KSCE J. Civil Eng*., **5**(2), 157-164.

Lian, C., *et al.* (2011), "The relationship between porosity and strength for porous concrete", *Constr. Build. Mater*., **25**(11), 4294-4298.

Mindess, S., *et al.* (2003), Concrete 2nd Editio, Upper Saddle River, NJ: Pearson Education, Inc.

Moayedi, H., *et al.* (2012), "Stabilization of organic soil using sodium silicate system grout", *Int. J. Phys. Sci*., **7**(9), 1395-1402.

Mohammadhassani, M., *et al.* (2014a), "An experimental study on the failure modes of high strength concrete beams with particular references to variation of the tensile reinforcement ratio", *Eng. Fail. Anal*., **41**, 73-80.

Mohammadhassani, M., *et al.* (2013), "Identification of a suitable ANN architecture in predicting strain in tie section of concrete deep beams", *Struct. Eng. Mech*., **46**(6), 853-868.

Mohammadhassani, M., *et al.* (2014b), "An evolutionary fuzzy modelling approach and comparison of different methods for shear strength prediction of high-strength concrete beams without stirrups", *Smart Struct. Syst*., **14**(5), 785-809.

Mohammadhassani, M., *et al.* (2015), "Fuzzy modelling approach for shear strength prediction of RC deep beams", *Smart Struct. Syst.*,**16**(3), 497-519.

Muhammad, B., *et al.* (2012), "Influence of non-hydrocarbon substances on the compressive strength of natural rubber latex-modified concrete", *Constr. Build. Mater*., **27**(1), 241-246.

Mui, E.L., *et al.* (2010), "Tyre char preparation from waste tyre rubber for dye removal from effluents", *J. Hazard. Mater*., **175**(1), 151-158.

Padhi, S. and Panda, K. (2016), "Fresh and hardened properties of rubberized concrete using fine rubber and silpozz", *Adv. Concrete Constr*., **4**(1), 49-69.

Paje, S., *et al.* (2010), "Acoustic field evaluation of asphalt mixtures with crumb rubber", *Appl. Acoust*., **71**(6), 578-582.

Paknahad, M., *et al.* (2018), "Shear capacity equation for channel shear connectors in steel-concrete composite beams", *Steel Compos. Struct*., **28**(4), 483-494.

Pelisser, F., *et al.* (2011), "Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition", *J. Cleaner Production*, **19**(6), 757-763.

Safa, M., *et al.* (2016a), "Potential of adaptive neuro fuzzy inference system for evaluating the factors affecting steel-concrete composite beam's shear strength", *Steel Compos. Struct.*, **21**(3), 679-688.

Safa, M., *et al.* (2016b), "Potential of adaptive neuro fuzzy inference system for evaluating the factors affecting steel-concrete composite beam's shear strength", *Steel Compos. Struct.*, **21**(3), 679-688.

Sajedi, F. (2012), "Effect of curing regime and temperature on the compressive strength of cement-slag mortars", *Constr. Build. Mater*., **36**, 549-556.

Sata, V., *et al.* (2016), "Properties of pervious concrete containing high-calcium fly ash", *Comput. Concrete*, **17**(3), 337-351.

Shahabi, S., *et al.* (2016), "Numerical analysis of channel connectors under fire and a comparison of performance with different types of shear connectors subjected to fire", *Steel Compos. Struct*., **20**(3), 651-669.

Shariat, M., *et al.* (2018), "Computational Lagrangian Multiplier Method using optimization and sensitivity analysis of rectangular reinforced concrete beams", *Steel Compos. Struct.*, **29**(2), 243-256.

Shariati, A. (2014), Behaviour of C-shaped Angle Shear Connectors in High Strength Concrete. M.SC, Jabatan Kejuruteraan Awam, Fakulti Kejuruteraan, Universiti Malaya.

Shariati, A., *et al.* (2012a), "Investigation of channel shear connectors for composite concrete and steel T-beam", *Int. J. Phys. Sci*., 7(11), 1828-1831.

Shariati, A., *et al.* (2014a), "Experimental assessment of angle shear connectors under monotonic and fully reversed cyclic loading in high strength concrete", *Constr. Build. Mater.*, **52**, 276-283.

Shariati, M. (2013), Behaviour of C-shaped shear connectors in steel concrete composite beams, PhD Thesis, Faculty of engineering University of Malaya, Kuala Lumpur, Malaysia.

Shariati, M., *et al.* (2012b), "Fatigue energy dissipation and failure analysis of channel shear connector embedded in the lightweight aggregate concrete in composite bridge girders", *Proceedings of the 5th International Conference on Engineering Failure Analysis*, 1-4 July 2012, Hilton Hotel, The Hague, The Netherlands.

Shariati, M., *et al.* (2010), "Experimental and analytical study on channel shear connectors in light weight aggregate concrete", *Proceedings of the 4th International Conference on Steel & Composite Structures*, 21 - 23 July, 2010, Sydney, Australia.

Shariati, M., *et al.* (2012c), "Experimental assessment of channel shear connectors under monotonic and fully reversed cyclic loading in high strength concrete", *Mater. Des.*, **34**, 325-331.

Shariati, M., *et al.* (2011a), "Shear resistance of channel shear connectors in plain, reinforced and lightweight concrete", *Scientific Res. Essays*, **6**(4), 977-983.

Shariati, M., *et al.* (2011b), "Assessing the strength of reinforced concrete structures through Ultrasonic Pulse Velocity and Schmidt Rebound Hammer tests", *Scientific Res. Essays*, **6**(1), 213-220.

Shariati, M., *et al.* (2011c), "Experimental and numerical investigations of channel shear connectors in high strength concrete", *Proceedings of the 2011 World Congress on Advances in Structural Engineering and Mechanics (ASEM'11+)*, Seoul, South Korea.

Shariati, M., *et al.* (2015), "Behavior of V-shaped angle shear connectors: experimental and parametric study", *Mater. Struct.*, 1-18.

Shariati, M., *et al.* (2016), "Comparative performance of channel and angle shear connectors in high strength concrete composites: An experimental study", *Constr. Build. Mater.*, **120**, 382-392.

Shariati, M., *et al.* (2011d), "Behavior of channel shear connectors in normal and light weight aggregate concrete (Experimental and Analytical Study) ", *Adv. Mater. Res.*, **168**, 2303-2307.

Shariati, M., *et al.* (2014b), "Fatigue energy dissipation and failure analysis of angle shear connectors embedded in high strength concrete", *Eng. Fail. Anal.*, **41**: 124-134.

Shen, W., *et al.* (2013), "Investigation on polymer–rubber aggregate modified porous concrete", *Constr. Build. Mater.*, **38**, 667-674.

Sinaei, H., *et al.* (2011), "Numerical investigation on exterior reinforced concrete Beam-Column joint strengthened by composite fiber reinforced polymer (CFRP)", *Int. J. Phys. Sci.*, **6**(28), 6572-6579.

Sinaei, H., *et al.* (2012), "Evaluation of reinforced concrete beam behaviour using finite element analysis by ABAQUS", *Scientific Res. Essays*, **7**(21), 2002-2009.

Soltani, M., *et al.* (2015), "Analysis of fatigue properties of unmodified and polyethylene terephthalate modified asphalt mixtures using response surface methodology", *Eng. Fail. Anal.*, **58**, 238-248.

Toghroli, A., *et al.* (2017), "Investigation on composite polymer and silica fume–rubber aggregate pervious concrete", *Proceedings of the 5th International Conference on Advances in Civil, Structural and Mechanical Engineering - CSM 2017*, Zurich, Switzerland.

Toghroli, A., *et al.* (2018), "A review on pavement porous concrete using recycled waste materials", *Smart Struct. Syst.*, **22**(4), 433-440.

Toghroli, A., *et al.* (2016), "Potential of soft computing approach for evaluating the factors affecting the capacity of steel–concrete composite beam", *J. Intel. Manufact.*, 1-9.

Topcu, I.B. (1995), "The properties of rubberized concretes", *Cement Concrete Res.*, **25**(2), 304-310.

Toutanji, H. A. (1996), "The use of rubber tire particles in concrete to replace mineral aggregates", *Cement Concrete Compos.*, **18**(2), 135-139.

Turatsinze, A., *et al.* (2005), "Mechanical characterisation of cement-based mortar incorporating rubber aggregates from recycled worn tyres", *Build. Environ.*, **40**(2), 221-226.

Vakili, A., *et al.* (2013), "Effects of using pozzolan and portland cement in the treatment of dispersive clay", *The Scientific World J.*, **2013**.

Voronina, N. (1997), "An empirical model for rigid frame porous materials with high porosity. ", *Appl. Acoust.*, **51**(2), 181-198.

Wang, J., *et al.* (2009). "Optimal placement of piezoelectric curve beams in structural shape control", *Smart Struct. Syst.*, **5**(3), 241-260.

Wang, J.Y., *et al.* (2012), "Stability of cenospheres in lightweight cement composites in terms of alkali–silica reaction", *Cement Concrete Res.*, **42**(5), 721-727.

Zhang, X., *et al.* (2002), "Study on impact-proof and abrasion-proof concrete in runway", *J. Nanjing Univ. Aeronautics & Astronautics*, **34**(2), 114-120.

Zheng, M.I., *et al.* (2007), "Physical and mechanical performance of porous concrete for drainage base", *J. Xi'an Univ. Sci. Technol.*, **4**, 017.

Ziaei-Nia, A., *et al.* (2018), "Dynamic mix design optimization of high-performance concrete", *Steel Compos. Struct.*, **29**(1), 67-75.

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