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Strength Properties of Pervious Concrete Made with Locally Produced Recycled Coarse Aggregate

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Abstract **-** Pervious concrete is a special type of concrete that addresses critical environmental issues and supports green, sustainable construction. In such concrete, little or no sand is employed in the mix in order to allow the formation of considerable void content leading to high permeability. In this study, seven pervious concrete mixes made with recycled coarse aggregate and containing different amount of natural fine aggregate are tested in the laboratory for their strength. The source of the coarse aggregate is demolished old concrete buildings in the United Arab Emirates. One of the mixes contains 100% natural coarse aggregate without natural sand, another 100% recycled coarse aggregate without natural sand, and the remaining 5 mixes include both recycled coarse aggregate and fine natural aggregate such that the amount of fine-to-coarse aggregate is 1.5-11.7%. Results of the study revealed that that the use of recycled coarse aggregate in pervious concrete without fine aggregate reduced the compressive strength by 36% and tensile strength by 57%. Replacing 4.7% of the recycled coarse aggregate with natural sand in such concrete helped in restoring the compressive strength to the level of the control mix that contained natural coarse aggregate. Likewise, replacing 11.7% of the recycled coarse aggregate with natural sand in concrete mix aided in restoring the split cylinder tensile strength to the level of the control mix that contained natural coarse aggregate. There is a relationship between compressive and tensile strengths, of which a lower bound can be reasonably predicted by models proposed for pervious concrete in the literature. The study confirms the feasibility of using recycled aggregate in pervious concrete mixes if about 10% natural fine aggregate is utilized in the mix as replacement of the recycled coarse aggregate.

Keywords**:** compressive strength; pervious concrete; recycled coarse aggregate; split cylinder strength; sustainability.

1. Introduction

Due to its countless benefits, concrete is the most commonly used material in civil infrastructure systems. In particular, low strength concrete is often utilized in the construction of earth dams, retaining walls, slabs-on-grade and other applications, such as in the form of pervious concrete in rigid pavement roads, recreational parks and parking lots. ASTM defines pervious concrete as "hydraulic-cement concrete proportioned with sufficient, distributed, interconnected macroscopic voids that allow water to flow through the material under the action of gravity alone" [1]. Similar to conventional concrete, pervious concrete is proportioned from a mixture of cement, coarse aggregates and water, but includes little or no sand. The most valuable asset of this type of concrete is its high permeability which aids water to infiltrate through the voids. The coarse aggregate utilized in pervious concrete is to some extent of similar size and bonded together by a thin cement water paste. The use of uniformly graded aggregate in the concrete mix leads to the establishment of substantial extent of interconnected voids in the concrete which helps in percolation of water through it under gravity [2].

Pervious concrete has many advantages, such as reducing the amount of rain seeping into storm sewer pipes, recharging groundwater to high aquifer levels, channelling water to plants in urban settings, lessening the impact of pollutants that can harm the ecosystem, and eliminating hydrocarbon contamination from asphalt and sealers when used in pavements. Detailed information on porosity, permeability and transport processes in pervious concrete are included in the work of Maher Al-Jabari [3]. From an economic point of view, pervious concrete has lower construction costs because it eliminates the installation of curbs, gutters, drain inlets, piping, and retention basins. Moreover, it also the use of existing sewer systems by reducing the need for increasing the size of existing storm sewer systems to accommodate new construction. Furthermore, it increases land use because it eliminates the purchase of extra land for housing large water-retention and filtration systems. Life-cycle costs are also lower with pervious concrete due its long-life expectancy, which matches that of conventional concrete [4].

Sustainable construction requires using recyclable and renewable materials and components in structures while reducing energy consumption and waste. The nature and form of transportation and production of construction materials can substantially affect the amount carbon emissions into the natural environment. Mining raw materials can lead deforestation, destruction habitat, pollution of environment, erosion of soil, loss of biodiversity, and change in climate. Cement plants release 1.6 billion metric tons of carbon dioxide each year, and have more than doubled since the turn of the century (www.statista.com). Because cement is only a portion of the ingredients of concrete, production of a one cubic yard of concrete is accountable for releasing about 400 lbs of carbon dioxide (www.cement.org).

Recycled aggregate pervious concrete, referred to in this study as RAPC, is a type of pervious concrete that replaces the natural coarse aggregate with recycled one. While the recycled aggregate could come from different sources, the most common origin is concrete structures demolishing waste. Such recycled aggregate includes in addition to the original aggregate some hydrated cement paste, which decreases the specific gravity and increases the absorption due to its high porosity relative to the natural aggregate.

This study is concerned with the determination and analysis of mechanical properties of pervious concrete made with locally produced recycled coarse aggregate from concrete rubble waste generated in the United Arab Emirates (UAE) and varying amount of natural fine aggregate. Specifically, it addresses the compressive and tensile strengths, as well as the correlation between the two strengths, and compares the response of the recycled aggregate pervious concrete to corresponding concrete made with natural coarse aggregate.

2. Previous Studies

While there is an abundance of published research in the existing literature on pervious concrete mix design methods, mechanical properties and construction procedures, research on the incorporation of recycled aggregate in this type of concrete is relatively scarce. In this section, we summarize some of the available studies that have addressed this topic. For example, Brasileiro et al. [5] studied the impact of recycled aggregates and silica fume use on the performance of pervious concrete and found that the sample with 50% recycled aggregates exhibited the highest value, with a 10% increase in permeability over the control natural aggregate sample. Samples with 40%, 50%, and 60% recycled aggregates demonstrated reductions of 48%, 56%, and 52%, respectively, in the compressive strength compared to the control specimens. The sample with 40% recycled aggregate exhibited less cracks and higher resistance to load than the other samples. Fan et al. [6] used tests to investigate the water purification traits of carbonated RAPC. They determined that recycled aggregate was more beneficial than natural aggregate for contaminant adsorption and micro-organism progression. They also found that while the purification capability of RAPC was slightly worse than concrete utilizing natural aggregate, its mechanical properties and alkalinity were better. Yang et al. [7] explored the void clogging performance of RAPC and reached the conclusion that the use of recycled aggregate reduced the effective porosity and water permeability of such concrete. Also, RAPC with funnel-shaped pore distributions were more likely to be clogged by dusty soil and the clogging mainly occurred within 33 mm thick layer of the concrete. Lima et al. [8] investigated the parameters of RAPC containing a new combination of superplasticizer and Hydroxypropyl methylcellulose admixtures. Findings of the study showed that the use of 50% recycled coarse aggregate for paste contents of 15.2% and 18.3% attained an enhancement in mechanical properties by increasing the connectivity and pore size, without greatly impacting the permeability. The new combination of admixture improved the interfacial transition zone of RAPC and enabled hydraulic-mechanical properties similar to concrete with natural aggregate. Vieira et al. [9] studied that effect of recycled aggregate replacement ratio and fly ash content on behaviour of pervious concrete. The found out that the use of 10% fly ash in pervious concrete with 75% of recycled aggregate can increase clogging by 6% compared to the reference concrete. Also, the increase of the recycled aggregate content in pervious concrete aided in the enhancement of surface abrasion. In addition, tests on the microstructure demonstrated an improved correlation between the macrostructural characteristics and the void content. Wang et al. [10] examined the strength improvement of RAPC using cement paste redistribution method that is based on silane polymer emulsion treatment. Findings of the investigation showed that the treatment greatly enhanced the strength of concrete with causing little effect on permeability. Meso-structure assessments validated the concentration of more cement paste between neighbouring aggregate at points of contact. Yap et al. [11] used results to compare the properties of pervious concrete with blended natural aggregate and recycled concrete They concluded that RAPC have lower mechanical properties due to debonding around the adhered mortar on recycled coarse aggregate. Greenhouse gases evaluation revealed that the CO2 emission of 100% RAPC mix was 24% lower the control mix that included natural aggregate. Ibrahim et al. [12] explored the hydraulic and strength properties of pervious concrete made with large quantities of aggregate from construction and demolition waste. Results of the study showed that the mix that had w/c=0.35 gave the best mechanical parameters. Also, use of recycled fine aggregate in the pervious concrete mix helped enhance the compressive by 7% and splitting tensile strength by 37%. Comparing between RFA and river sand, microscopic analyses showed that the adhered mortar on recycled aggregate reduced its crack change capability in enhancing the pervious concrete's capacity.

3. Characteristics of the Materials

The coarse aggregate used in the study was obtained from a governmental recycling company, called Beeah, with the goal of promoting sustainability-based initiatives in the UAE. The construction and waste demolition division of Beeah processes annually approximately 0.5 million metric tons of rubbles from new construction and demolition of old structures. The facility produces aggregate in various sizes and shapes, of which the type that is used in the study is shown in Figure 1, that can be utilized later in roads and buildings.

Fig. 1: Recycled coarse aggregate produced by Beeah, UAE, and used in the study.

Particle gradation of the obtained crushed old concrete from Beeah was accomplished by sieve analysis in accordance with ASTM C-136 [13]. The size of the recycled coarse aggregate (RCA) in this research varied between 6.73 and 15.9 mm, as shown in Figure 1. For uniformity, the particle size distribution for the coarse natural aggregate (NA) was selected to closely match that of the RCA.

Fig. 2: Recycled coarse aggregate size distribution.

Using ASTM C-29 [14], the bulk specific gravity, saturated-surface-dry bulk specific gravity, and apparent specific gravity for the RCA were 2.46, 2.58, and 2.77, respectively. The corresponding values for the NA were 2.44, 2.54 and 2.70, respectively. As expected, the water absorption of the RCA was higher by 13% than that of the NA (4.53% versus 3.99). The LA abrasion values in accordance with ASTM C-131 [15] for the RCA and NA were respectively 31.9% and 24.0%, whereas the crushing values following the BS 812: Part 110 standard [16] were correspondingly 24.1% and 19.1%. Even though the abrasion and crushing results for the RCA were inferior to those of the NA, they exceeded the minimum 30% limit needed for use in structural applications. For the mixes that contained natural fine aggregate, dune sand with fineness modulus equal to 0.74 was used. All pervious concrete mixes utilized ordinary Portland cement that was composed of SiO2, Al2O3, Fe2O2, CaO, MgO, SO3, Na2O and LOI. No alternative cementitious materials or admixtures were used in all the concrete mixes.

4. Methodology

The mix design of the pervious concrete was done in accordance with the provisions of the ACI 522.1 [17]. In a typical concrete mix, the amount of water was 110 kg/m^3, quantity of cement was 356 kg/m^3, mass of natural coarse aggregate was either 0 or 1599 kg/m^3, mass of recycled coarse aggregate was either 0 or 1431-1599 kg/m^3, and mass of natural fine aggregate was between 0-168 kg/m^3. The ratio of water-to-cement was 0.309, cement-to-coarse aggregate was 1:4.49-1:4.02, and fine-to-coarse aggregate was 0:1-1:8.5. In this study, 7 different mix designs were produced with water content of 110 kg/m^3, cement of 356 kg/m^3, coarse aggregate ranging 1430-1599 kg/m^3, and fine aggregate between 0 and 168 kg/m^3. Table 1 shows the proportions details of 7 pervious concrete mixtures considered in the study. Mix 1 is a control sample that includes coarse natural aggregate, but no coarse recycled aggregate or fine aggregate. Mix 2 is another control sample that includes recycled coarse aggregate, but no fine aggregate. Thereafter, each mix (that is Mix 3, 4, 5, 6, or 7) has some amount of the RCA replaced with the same amount of natural fine aggregate. Figure 3 shows samples of pervious concrete prior to testing.

Table 1: Mix design proportions of the pervious concrete.

Ingredients (kg/m^3)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Water	110	110	110	110	110	110	110
Portland Cement	356	356	356	356	356	356	356
Natural Coarse Aggregate	1599	0	0	0	0	0	0
Recycled Coarse Aggregate	0	1599	1575	1551	1527	1479	1431
Natural Fine Aggregate	0	0	24	48	72	120	168
% of Fine-to-coarse Aggregate	0	0	1.5	3.1	4.7	8.1	11.7

Fig. 3: Pervious concrete samples ready for testing.

In this study, the compressive strength of the pervious concrete was obtained using a high-stiffness compression machine at a loading rate of 0.25 MPa/second. The compressive strength was determined by dividing the maximum load that a 150 mm by 300 mm cylindrical specimen can support while standing up on its base prior to collapse by the cross-sectional area of the base. The split cylinder tensile strength of the concrete was found by applying a load on a 150 mm by 300 mm cylinder while sitting on its side through bearing strips at a rate equal to 0.1 MPa/second. To obtain the split cylinder tensile strength from the test, the maximum load supported by the specimen prior to collapse is divided by one-half the surface area of the cylinder. Figure 4 shows the laboratory test setups for determining the compressive and split cylinder tensile strengths.

Fig. 4: Determination of compressive and split tensile strengths of pervious concrete.

5. Results

In this section, the results of the experimental testing of the 7 pervious concrete mixes are presented and discussed. The compressive and split cylinder tensile strengths for the pervious concrete at the age of 28 days are shown in Table 2. Each data point represents the average outcome of 3 samples.

Table 2: Compressive and tensile strength results of the pervious concrete.

Mechanical Properties (MPa)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Compressive Strength	7.08	4.53	4.94	5.96	7.03	7.14	7.17
Split Cylinder Tensile Strength	1.56	0.67	0.97	0.98	1.00	1.34	1.58

With regard to the compressive strength, the test results showed that 100% replacement of the natural coarse aggregate with recycled one caused the compressive strength of pervious concrete to reduce by 36%, from $(f'_c)_{Mix1}$ = 7.08 MPa to $(f'_c)_{Mix2}$ = 4.53 MPa. This is because the strength, surface texture and bond characteristics of the recycled coarse aggregate are inferior to those of the virgin aggregate. Specifically, the lower abrasion results (24% versus 31.9%) and crushing values (19.1% versus 24.1%) of the recycled aggregate compared to the natural aggregate have contributed to the 36% decrease in compressive strength of the pervious concrete. Concerning the influence of adding fine aggregate to pervious concrete mixes on the compressive strength, we examine the results of Mixes 2-7, shown in Fig. 5, which contain fine aggregate in varying amount. The results indicate that the effect of adding fine aggregate on compressive strength is most significant when the fine-to-coarse aggregate percentage is less than 5%. Beyond the 5% limit, any added quantity of fine aggregate as a replacement of coarse aggregate has negligible consequence on strength. Note that at the 5% fine aggregate replacement limit and beyond, the compressive strength of the RAPC is restored to that of corresponding PC with natural aggregate.

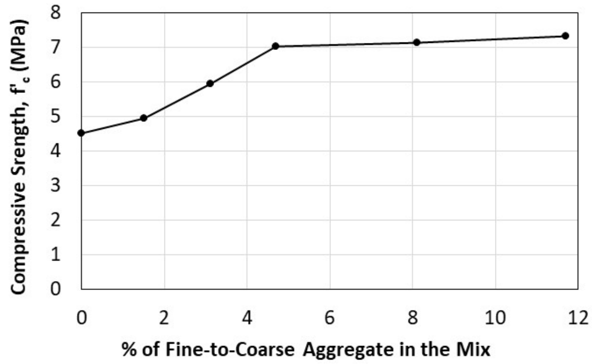

Fig. 5: Effect of replacing recycled coarse aggregate with natural fine aggregate on compressive strength.

Concerning the tensile strength, findings of the test outcomes revealed that 100% replacement of the natural coarse aggregate with recycled aggregate triggered the split cylinder strength of pervious concrete to reduce by 57%, from $(f'_{ct})_{Mix1}$ = 1.56 MPa to $(f'_{ct})_{Mix2}$ = 0.67 MPa. Although concrete containing recycled aggregate is generally weaker in tension when compared with concrete containing natural aggregate, the observed drop in this study is very steep and larger than the corresponding 36% drop in the compressive strength. To study the effect of utilizing fine aggregate to pervious concrete mixtures on its tensile strength, we compare the results of Mixes 2-7, which include fine aggregate in varying amount, as presented in Fig. 6. The results exhibit the positive influence on the tensile strength of incorporating fine aggregate into pervious concrete mixes. Even a small replacement fraction of the recycled coarse aggregate with natural fine aggregate can enhance the tensile strength by a large percentage relative to concrete containing only RCA. In fact, adding 11.7% of fine aggregate as replacement of RCA into a pervious concrete mix can help restore the tensile strength, $(f'_{ct})_{Mix7}$ = 1.58 MPa, to that of pervious concrete made with 100% natural coarse aggregate, $(f'_{ct})_{Mix1}$ = 1.56 MPa.

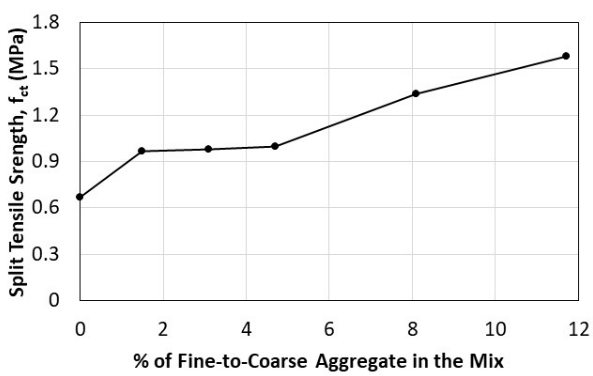

Fig. 6: Effect of replacing recycled coarse aggregate with natural fine aggregate on tensile strength.

Many researchers have sought more accurate relationships between the concrete compressive and tensile strengths than what is available in concrete codes and specifications, see for example the work of Bin Ahmad et al. for conventional concrete [18] and Gaedicke et al. for pervious concrete [19]. Experience has shown that relationships between compressive and corresponding tensile strengths for conventional concrete are not applicable for pervious concrete because the later is relatively weaker in tension due to lack of adequate paste. Figure 7 shows a scatter diagram for the pervious concrete mixes that contain recycled aggregate with various fractions of natural fine aggregate. In addition to the points that represent the experimental results, the plot includes two lines, a straight line from the linear regression analysis ($f_{ct} = 0.22f'_c - 0.26$) and the equation of the curve proposed by Gaedicke et al. [19] ($f_{ct} = 0.181(f'_c)^{0.875}$), in which both f_{tc} and f'_c are in MPa. For the data points that were generated in the study, it is clear that Gaedicke et al's proposed equation represents a lower bound on the obtained data. Nevertheless, this equation seems reasonable since theoretical formulations are supposed to be conservative predictions of an unknown outcome.

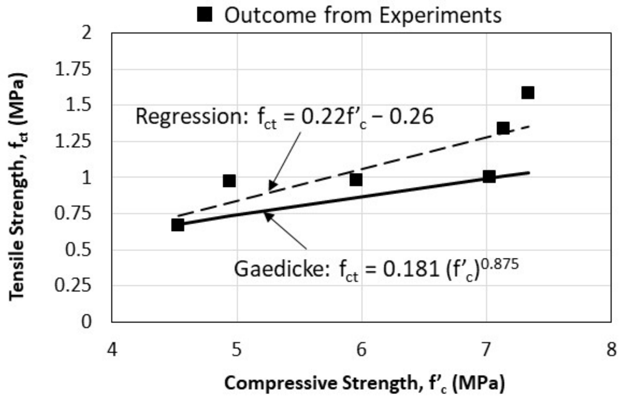

Fig. 7: Relationship between compressive and tensile strengths of the considered pervious concrete.

6. Conclusion

Results of the study on pervious concrete that contains 100% recycled coarse aggregate with and without natural sand leads to the following conclusions:

1. Even though the abrasion and crushing results for the RCA were inferior to those of the NA, they exceeded the minimum 30% limit needed for use in structural applications.
2. Use of recycled coarse aggregate in pervious concrete exclusive of fine aggregate decreased the compressive strength by 36% and tensile strength by 57%.
3. Exchanging 4.7% of the recycled coarse aggregate with natural sand in the pervious concrete mix helped in restoring the compressive strength to the level of the control mix that contained 100% natural coarse aggregate.
4. Exchanging 11.7% of the recycled coarse aggregate with natural sand in the pervious concrete mix aided in restoring the split cylinder tensile strength to the level of the control mix that contained 100% natural coarse aggregate.
5. There is a relationship between the compressive and tensile strengths, of which a lower bound can be reasonably predicted by the model proposed by Gaedicke et al. [19].
6. The study showed that it is possible to utilize locally produced recycled coarse aggregate from the UAE in pervious concrete mixes if approximately 10% natural fine aggregate is utilized in the mix as replacement of the recycled coarse aggregate.

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References

[1] ASTM C125−15b "Standard Terminology Relating to Concrete and Concrete Aggregates," ASTM: West Conshohocken, PA, USA, 2015, 8 pages.
[2] Priyaranjan Pal, Shalinee Shukla, and A. K. Ranjan, "Performance of Pervious Concrete with Recycled Concrete Aggregate," Indian Concrete Journal, Vol. 91, Issue 1, January 2017, pp.86-92.
[3] Maher Al-Jabari. "Integral Waterproofing of Concrete Structures - Advanced Protection Technologies of Concrete by Pore Blocking and Lining," Woodhead Publishing Series in Civil and Structural Engineering, 2022, 468 pages.
[4] https://www.concretenetwork.com/pervious/how_it_works.html, accessed on January 17, 2024.

[5] Kelly Patrícia Torres Vieira Brasileiro, Bacus de Oliveira Nahime, Elton Carvalho Lima, Michell Macedo Alves, Walkíria Pederiva Ferreira, Igor Soares dos Santos, César Pereira Bezerra Filho, and Idalci Cruvinel dos Reis, "Influence of recycled aggregates and silica fume on the performance of pervious concrete," Journal of Building Engineering, Volume 82, April 2024, 14 p. 108347.
[6] Meng Fan, Bowen Tang, Xianchen Sun, Xiangli He, and Linjuan Yuan "Experimental study on the water purification performance of carbonated recycled aggregate pervious concrete," Construction and Building Materials, Volume 406, 24 November 2023, 133392.
[7] Jingyu Yang, Yinchuan Guo, Vivian W.Y. Tam, Jingjing Tan, Aiqin Shen, Jianfeng Zhang, Chong Zhang, and Zhenghua Lyu, "Research on pore-clogging behavior and mechanism in pervious concrete prepared with recycled aggregate," Construction and Building Materials, Volume 384, 27 June 2023, 131420.
[8] Geannina Terezinha dos Santos Lima, Janaíde Cavalcante Rocha, and Malik Cheriaf, "Investigation of the properties of pervious concrete with a recycled aggregate designed with a new combination of admixture," Construction and Building Materials, Volume 340, 18 July 2022, 127710.
[9] Gabrieli Lazzari Vieira, Jéssica Zamboni Schiavon, Pietra Moraes Borges, Sérgio Roberto da Silva, and Jairo José de Oliveira Andrade, "Influence of recycled aggregate replacement and fly ash content in performance of pervious concrete mixtures," Journal of Cleaner Production, Volume 271, 20 October 2020, 122665.
[10] Tiejun Liu, Zhongzhen Wang, Dujian Zou, Ao Zhou, and Junze Du, "Strength enhancement of recycled aggregate pervious concrete using a cement paste redistribution method," Cement and Concrete Research, Volume 122, August 2019, Pages 72-82.
[11] Soon Poh Yap, Paul Zhao Chiat Chen, Yingxin Goh, Hussein Adebayo Ibrahim Kim Hung Mo, and Choon Wah Yuen, "Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates," Journal of Cleaner Production, Volume 181, 20 April 2018, Pages 155-165.
[12] Hussein Adebayo Ibrahim, Yingxin Goh, Zheng Ann Ng, Soon Poh Yap, Kim Hung Mo, Choon Wah Yuen, and Fuad Abutaha, "Hydraulic and strength characteristics of pervious concrete containing a high volume of construction and demolition waste as aggregates," Construction and Building Materials, Volume 253, 30 August 2020, 119251.
[13] ASTM C136-06, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM: West Conshohocken, PA, 2009.
[14] ASTM C29/C29M-97, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate, ASTM: West Con-shohocken, PA, 2009.
[15] ASTM C131-06, Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine, ASTM: West Conshohocken, PA, 2009.
[16] British Standard BS 812-110:1990, Testing aggregates — Part 110: Methods for determination of aggregate crushing value (ACV), BSI, 389 Chiswick High Road London W4 4AL, 1990.
[17] ACI 522.1: Specification for Construction of Pervious Concrete Pavement, American Concrete Institute, Farmington Hills, Michigan, USA, 2020, 8 pages.
[18] Farabi Bin Ahmed, Khan Abid Ahsan, Tasnuva Shariff, and Shafin Rahman Meem, "Formulation of polynomial equation predicting the splitting tensile strength of concrete," Materials Today: Proceedings, Volume 38, Part 5, 2021, Pages 3269-3278.
[19] Cristián Gaedicke, Anthony Torres, Khanh C.T. Huynh, and Armando Marines, "A method to correlate splitting tensile strength and compressive strength of pervious concrete cylinders and cores," Construction and Building Materials, Volume 125, 30 October 2016, Pages 271-278.