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Surface Area Model to Assess the Plastic Aggregate Concrete Properties

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Abstract: In this study, a model was proposed based on calculating the total surface area of aggregate to assess fresh density, compressive, and splitting tensile strengths of plastic aggregate (PA) recycled concrete. The key factor is the change in the total surface area of the natural aggregate by the PA. For a given PA volume, the change in the property could be assessed. The prediction well depends on the natural and plastic aggregates distribution size, specific gravity, and bulk density. The proposed model prediction was accurate when applied to high-strength, and lightweight concretes. The reason is attributed to the relatively good bond between PA and hardened cement paste in these concretes. However, for the majority of concrete mixes investigated, the model moderately underestimated strength loss, and this underestimation could be attributed to the PA- hardened cement paste bond deficiency. An attempt was made to assess the bond deficiency parameter for a more accurate prediction.

نموذج المساحة السطحية لتقييم خصائص الكونكريت ذو الركام البلاستيكي

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الخلاصة

في الدراسة الحالية تم تقديم نموذج تحليلي لحساب المساحة السطحية للركام لغرض تقييم صفات الكثافة الطرية، مقاومة الانضغاط، ومقاومة الشد الانشطارية للخرسانة المعاد تدويرها الحاوية على ركام البلاستك. ان مفتاح الحل في القضية هو تغير المساحة السطحية للركام الطبيعي عند اضافة ركام البلاستك للخلطة ومن خلاله ولأي نسبة حجمية للركام البلاستك يمكن تحديد التغير في الخاصية المحددة. ان التنبؤات يعتمد في الاساس على التدرج الحجمي، الوزن النوعي والكثافة الكلية لكل من الركام الطبيعي والصناعي. وقد لوحظ بان تنبؤات الانموذج المقدم دقيقة عند تطبيقها على خرسانة عالية المقاومة وخرسانة خفيفة الوزن. ان السبب في ذلك هو جودة الربط بين سطح ركام البلاستك وعجينة السمنت المتصلبة للنوعين من الخرسانة. ومع ذلك لمعظم الخلطات الخرسانية التي تم دراستها وجد بان الانموذج المقدم يتنبأ تحت المطلوب النقصان الواقع في المقاومة والسبب في ذلك يعزى الى القصور في الربط بين حبيبات البلاستك وعجينة السمنت المتصلبة. تم المحاولة في البحث الحالي لتقييم عامل قصور الربط للحصول على تنبؤات أكثر دقة.

الكلمات الدالة: مساحة السطح للركام، قوة الضغط، الكثافة الطرية، الركام الطبيعي، الركام البلاستيكي، مقاومة الشد الانشطاري.

1.INTRODUCTION

Currently, used plastics are mainly categorized into seven popular types. Commonly used plastics are acrylic or polymethyl methacrylate (PMMA), polycarbonate (PC), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PETE or PET), polyvinyl chloride (PVC), and acrylonitrile-butadiene-styrene (ABS). The highly consumed plastics worldwide are usually accompanied by a massive amount of solid waste that should be recycled to avoid environmental pollution. This pollution will create many problems; it reduces the environment's natural beauty, causes confinement and death of aquatic organisms, and blockage of sewage systems in cities, especially in developing countries, causing other illnesses. Researchers estimate that over 40% of the world's waste is incinerated. However, burning plastics and other wastes release toxic substances such as heavy metals, persistent organic pollutants (POPs), and other toxic chemicals into the atmosphere. To avoid releasing toxic substances, researchers have worked to find out the best route of plastic waste management to save the environment against further pollution. However, recycling virgin plastic to make a new product is accompanied by a fate known as down-recycling, which results in the plastic being used for low-quality materials compared to its original use [1]. It must be emphasized that to recycle solid plastic, and there is a need for plasticizers. In developing countries, a low-cost plasticizer is attempted, and this sort of material is categorized as cancerous and may cause health problems. Alternatively, recycling shredded plastic as aggregate or fiber for concrete production may have a promising future. If plastics are used as an aggregate in concrete, the response post-peak becomes more ductile because the plastic particle absorbs energy [2]. Using plastic aggregate instead of natural sand will lead to strength loss, depending on the replacement level. However, tests show a shortage in compressive strength loss, in which records indicate a very low compressive strength loss and even strength enhancement when a low ratio of plastic aggregate is added to concrete [3, 4]. Knowing that due to the low density of the plastic particles, the produced concrete becomes lightweight. Further, there is an excellent occasion to construct a composite section based on two different concrete types, using plastic aggregate concrete as an infill core between two strong outer skins (or sandwich panels). This novel composite section may have a promising future in the precast concrete industry. However, this topic is relatively new, and the relevant researches are quite limited. Furthermore, records [5] have shown that using plastic aggregate instead of natural sand can enhance the impact strength of concrete.

2. STATE-OF-ART REVIEW

It is important here to discuss the effect of plastic aggregate shape and size on the residual properties of concrete as an introduction to the proposed aggregate surface area model. The effect of different plastic ratios as a fine aggregate replacement for a given type of plastic aggregate used was investigated by many researchers, such as Mohammed et al. [2], Al-Hadithi and Alani [6], and Kou et al. [7]. However, there are several experimental attempts [8-12] to investigate the role of plastic aggregate particle size and shape on some essential properties of recycled concrete. Below, the results of previous experimental works studied some key recycled concrete properties are presented and discussed. One of the early attempts was conducted by Marzouk et al. [13] in 2007. The authors investigated compressive strength, flexural strength, and elastic modulus of concrete of natural sand replaced by 2%, 5%, 10%, 15%, 20%, 30%, 50%, 70%, and 100% PET aggregate of three maximum sizes: 0.1, 0.3, and 0.5 cm. There was slight compressive strength enhancement when larger sizes of plastic aggregate were added by 5%, followed by strength loss with increasing the plastic aggregate (PA) volume. Their results indicated that using smaller-size PA led to a higher compressive strength loss regardless of the PA volume in the mix. The behavior of the PA concrete in flexure was similar to that in compression concerning the effect of particle size on the strength loss. The elastic modulus of concrete followed the same rule of compressive and flexural strengths. Also, using PA aggregate of the maximum size of 5 mm had better action in concrete than with smaller aggregate sizes in an experimental study, Saikia and de Brito [10] tested concrete with sand replaced by three types of plastic aggregate: coarse particle (PC), fine particle (PF), and heat-treated pellet (PP). The test data showed that as the plastic content in the mix increased to 15%, there was a need to increase the w/c ratio to maintain workability in terms of slump, indicating the slump reduction with increasing plastic content. There was a need to use a higher w/c ratio for coarser plastic particles than finer particles to maintain nearly the same workability. Also, the w/c ratio for pellet particles was lower than that of the flaky PET particle aggregate. These results clearly indicated the change of workability with changing the shape and size of the plastic aggregate, in which using pellet particle aggregate caused higher workability compared with the flaky PET particles. The researchers observed a continuous reduction of the compressive strength with increasing the plastic aggregate content, being increased with increasing the plastic size and the particles' flakiness. Their strength loss was relatively high, i.e., 65% strength loss of concrete using 15% coarse plastic particles tested at 28 days. The heat-treated, thick pellets' performance was better than flaky plastic particles to control strength loss regardless of plastic ratio and curing time. Further, Albano et al. [11] investigated the concrete slump with natural sand replaced by 10% and 20% PET aggregate of 1.14 cm, 0.26 cm, and a combination of both sizes. The results showed a reduction in the slump with increasing the PA ratio. In general, using coarse particle plastic aggregate caused more slump loss than the slump of mixes containing finer-graded PET particles. They also investigated the compressive strength of concrete at the ages of 7, 14, 28, and 60 days. Results showed a compressive strength loss with increasing PET aggregate ratio in concrete, increasing the plastic particle size for concrete mixes with w/c ratios of 0.5 and 0.6. Furthermore, Hannawi et al. [9] tested cement mortar made of natural sand partially replaced with polycarbonate (PC) and polyethylene terephthalate (PET). Various volume fractions of sand (3%, 10%, 20%, and 50%) were replaced by the same volume of PA. Compressive strength gradually decreased with increasing plastic aggregate in the mortar. Although the maximum size of the PET aggregate was 10 mm and for PC was 5 mm, the test data showed a negligible difference between the two compressive strength losses. From the preceding presentation, the effect of plastic particle geometry or shape and size on the residual compressive strength of recycled concrete can be detected. On this base, any proposed equation for calculating the compressive strength and other concrete properties will be accurate after considering the effect of the aggregate particles' shape and size. This effect could be collected in the physical properties of the plastic particle, particularly specific gravity and bulk density besides particle size distribution. In the following sections, the outline of the aggregate surface area model to assess the residual properties of recycled concrete is described.

3.1.AGGREGATE SURFACE AREA MODEL FOR PA CONCRETE PROPERTIES

In this proposed model, the effect of plastic aggregate particles' size and shape and even surface smoothness are included to assess accurately the fresh density, compressive strength, and splitting tensile strength of the PA concrete. The authors believe that the proposed model is a new attempt to assess the properties of recycled concrete containing PA by calculating the surface area of natural and PAs. The change of a surface area of a relatively strong particle aggregate with a weak plastic particle one is a crucial factor representing the change in the structure of hardened concrete leading to the change of the residual properties. The predictions are compared with the test data to check the model's validity. It was necessary to make some rational assumptions to work on the model because some experiments need more data related to PA properties, particularly PA thickness.

3.2. Calculation of Aggregate Surface Area

3.2.1 Surface area of natural aggregate

Several methods for calculating aggregate particles' total surface area or specific surface area (SSA) are available. SSA Assessment significantly affects the workability of concrete in the fresh state [14]. Another goal behind calculating the aggregate surface area is related to the design of an asphalt mixture [15]. The surface area's mathematical approximation is based on the assumption of a spherical shape of the particles. This approximation failed to consider the effect of shape and the square-cube law. For this purpose, Ghasemi et al. [14] worked on replacing the assumption of a spherical shape with that of Platonic solids as the representative shape to account for the angularity of aggregates. Carr et al. [16] developed an empirical method based on fractional dimension for estimating the surface area of aggregate particles not smaller than 1 mm. However, one of the most straightforward procedures for assessing SSA is given by Panda et al. [15]. They have proposed a simple procedure for calculating the total surface area of dust, coarse, and fine aggregates for hot mix asphalt (HMA) design. This procedure was based on: (a) calculating the mean size of the three components, (b) assuming the shape of the particle, cylindrical for coarse and fine aggregates and spherical for dust, (c) calculating the volume of the particle, (d) calculating the theoretical and actual number of particles in one m^3 of aggregate, and (e) calculating surface area of each particle and calculating total surface area in m^2. Below, the steps followed for calculating the total surface area of natural aggregate are presented. The surface area of the aggregate blend is calculated from the empirical formula given below:

$$S_{A\text{-}Total} = S_{A\text{-}CA} + S_{A\text{-}FA} + S_{A\text{-}DUST} \quad \textbf{(1)}$$

where $S_{A\text{-}CA}$ is the total surface area of coarse aggregate, $S_{A\text{-}FA}$ is the total surface area of fine aggregate, and $S_{A\text{-}DUST}$ is the total surface area of dust (particles below 75 microns) all in one cubic meter of a blend. Panda et al. [15] assumed a cylindrical shape for the coarse and fine aggregate particles and a spherical shape for the dust particle (see Fig. 1) to simplify the calculation of the total surface area aggregate in m^2/kg based on the surface area of one particle. In plastic aggregate recycled concrete, fine aggregate is mainly replaced with plastic, so a calculation of the total surface area of fine aggregate is given herein. The surface area of a fine aggregate with a particle size above 75 microns and below 4.75 mm is calculated as follows:

$$SA_{FA} = N_{FA}M_{A\text{-}FA}F_{FA} \quad \textbf{(2)}$$

where N_{FA} is the number of fine aggregate particles in one cubic meter of concrete $M_{A\text{-}FA}$ is the area of mean size of fine aggregate, and F_{FA} is the multiplying factor for unevenness of fine aggregate. For all i having sieve above 4.75 mm, the mean size of the fine aggregate (MS_{FA}) is given by [15]:

$$MS_{FA} = \sqrt{\frac{M_i MS_i^2}{\Sigma M_i}} \quad \textbf{(3)}$$

where M_i is the percentage mass of aggregates passing in (i +1)th sieve minus ith sieve, and MS_i is the mean size of (i +1)th sieve and ith sieve. The mean length of the fine aggregate particle is given by:

$$ML_{FA} = MS_{FA}\,(1\text{+Total flakiness \& Elongation}) \quad \textbf{(4)}$$

Fine aggregate particle is assumed to be cylindrical; the particle's surface area and volume are:

$$MA_{FA} = \pi MS_{FA}ML_{FA} + \frac{\pi}{2}MS_{FA}^2 \quad \textbf{(5)}$$

$$MV_{FA} = \frac{\pi}{4}MS_{FA}^2ML_{FA} \quad \textbf{(6)}$$

The number of particles per volume is related to the void's ratio in the following equation [15]:

$$N_{FA} = \frac{1}{MV_{FA}}\,(1-e)W_{FA} \quad \textbf{(7)}$$

where W_{FA} is the weightage of fine aggregate in the mix. The same procedure was followed for calculating the surface area of coarse aggregate ($S_{A\text{-}CA}$) having particle size above 4.75 mm. The dust surface area (particles below 75 microns) is given by

$$S_{A\text{-}DUST} = N_{DUST}M_{A\text{-}DUST}F_{DUST} \quad \textbf{(8)}$$

where N_{DUST} is the number of dust particles in one cubic meter of concrete, $M_{A\text{-}DUST}$ is the area of the dust particle's mean size, and F_{DUST} is the multiplying factor for unevenness of dust. The main difference between the dust and aggregate particles is that the dust shape was assumed to be spherical (see Fig. 1). On this base, the dust particle's area and volume are given in the following equations:

$$MA_{DUST} = \pi\, MS_{DUST}^2 \quad \textbf{(9)}$$

$$MV_{DUST} = \frac{\pi}{6}MS_{DUST}^3 \quad \textbf{(10)}$$

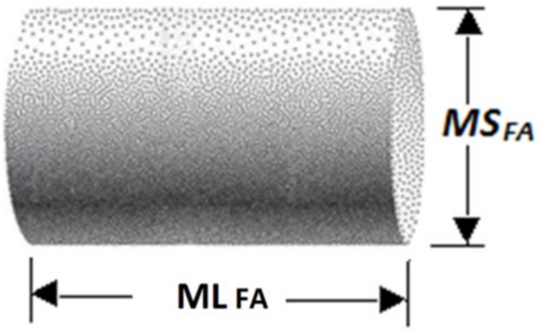
where MS_{DUST} is the mean dust size. The number of dust particles per volume is related to the voids ratio (e) in the following equation:

$$N_{DUST} = \frac{1}{MV_{DUST}}\,(1-e)W_{DUST} \quad \textbf{(11)}$$

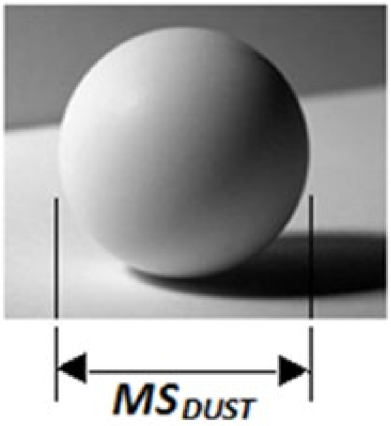
where W_{DUST} is the weightage of dust in the mix. It is noted that the number of particles depends on the void ratio of the bulk aggregate and dust and is calculated as follows [17]

$$e = 1 - \frac{\rho_A}{G.\rho_w} \quad \textbf{(12)}$$

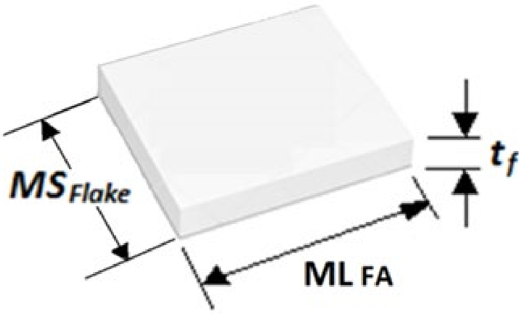
where ρ_A is the bulk density of aggregate (kg/m^3), G is the specific gravity of aggregate, and ρ_w is the water density(kg/m^3).



(a) Cylindrical particle



(b) Spherical particle (Dust)



(c) Flaky plastic aggregate

Fig. 1 Aggregate particle shape.

Panda et al. [15] used the following unevenness factors for the dust and aggregate:

- F_{DUST} =1.6 (additional sixty percent towards unevenness),
- F_{FA} = 1.6 x 2 = 3.2 (additional 100 percent towards unevenness compared to dust), and
- F_{CA} = 3.2 x 2 = 6.4 (additional 100 percent towards unevenness compared to fine aggregates).

Knowing that these factors are for aggregate used for hot asphalt mixture, mainly crushed stone aggregate. Based on the previous presentation, the steps below were followed to calculate the surface area of the dust particles:

a- The average size of dust passing 75 micron (MS_{DUST}) was taken as 0.04 mm, assuming spherical particles, and the theoretical volume of a dust particle (MV_{DUST}) was 3.35238 x 10^{-5} mm^3.
b- Calculate the voids ratio from Eq. (12).
c- From sieve analysis, dust content percentage (W_{DUST}) was determined, and the number of particles in one cubic meter (N_{DUST}) was determined from Eq. (11).
d- Having a surface area of 0.04 mm dust particle, equal to 0.005028571 mm^2 using Eq. (9), the total area of dust was determined (in m^2). Assume multiplying factor as 60%, higher on dust particles for uneven surface texture (which was 1.60), the total area of the dust (after correction) was calculated. The same procedure in steps a to d was followed for the fine aggregate of total weight on fine aggregate sieves (W_F) and coarse aggregate sieves (W_C) to calculate the two surface areas from Eq. (1), and the total surface area was determined.

For the recycled concrete made of natural river aggregate, the surface area calculation of dust is unrequired because the existence of dust particles is related to the crushed stone aggregate. Nearly all researchers that worked on concrete containing PA properties gave no information about dust particles in their sieve analysis.

3.2.2 Surface area of PA

The shape of a heat-treated plastic pellet could be considered cylindrical similar to that of natural coarse and fine aggregates. Also, any flaky particle of mean size below the thickness of plastic flakes was treated as pellets. The main difference between a plastic pellet and a natural aggregate is related to their surface texture. As mentioned before, unevenness factors of 3.2 for fine aggregate were recommended; however, due to the smooth surface of a plastic particle, as the author believes, there is no need to magnify the calculated area such as that done for natural aggregate. On this base, a high surface area is reduced by replacing the natural aggregate with a plastic one. Consequently, there was a lower total bond area of embedded plastic-natural particles with cement paste than that of natural aggregate with cement paste. Using plastic flakes of thickness smaller than its mean size (see Fig. 1c) should be separately treated. In this way, the effect of the particle's shape could be well included to assess the surface area accurately. In general, the plastic flakes used by some researchers, such as Kou et al. [7] (obtained from shredding PVC pipe of about 3 mm thickness), could be treated as pellet particles because the thickness was relatively large. The flake particles' surface area and volume are given by the two equations below:

$$MA_F = 2\ ML_F{*}MS_F \quad \textbf{(13)}$$

$$MV_F = t_F{*}\ ML_F{*}MS_F \quad \textbf{(14)}$$

where MA_F is the mean surface area of the flake, MV_F is the mean volume of the flake, t_f is the flake thickness, MS_F is the mean size of the flake, and ML_F is the mean length of the flake.

3.3. Calculation of Fresh Density Loss

The first application of the surface area model is the prediction of fresh concrete density. The initial unit weight of the control mix without plastic aggregate (in kg/m3) is given by

$$W_i = W_w + W_c + W_{CA} + W_S \quad \textbf{(15)}$$

The final weight of fresh concrete containing PA as a fine aggregate replacement (in kg/m^3) is given by

$$W_f = W_w + W_c + W_{CA} + W_S \left[\frac{RN_p w_{pp} + (1-R)N_s w_{ps}}{N_s w_{sp}}\right] \quad \textbf{(16)}$$

where W_w is the weight of water, W_c is the weight of cement, W_{CA} is the weight of coarse aggregate, and W_s is the weight of sand, all in kg/m^3. R is the ratio of sand replacement with PA. N_p is the number of PA particles in one cubic meter of aggregate, w_{pp} is the weight of one PA particle, N_s is the number of sand particles in one cubic meter of aggregate, and w_{ps} is the weight of one particle of sand. Results are represented in terms of fresh density ratio, calculated by dividing W_f by W_i.

3.4. Calculation of Strength Loss

In this proposed model, it is assumed that there was no compressive strength enhancement due to natural aggregate replacement with plastic, and there was always a strength loss. The calculation of the strength loss was based on the fact that a portion of the active surface area of the natural aggregate was replaced with the non-active weak surface area provided by the PA being increased with increasing the replacement ratio. For calculating plastic surface area, essential properties of plastic material of specific gravity and bulk density are included through the calculation of the void's ratio given in Eq. (12). On this base, the normalized residual compressive strength loss was assumed to depend on the change of surface area (modified surface area to basic surface area ratio) given by:

$$\frac{f'_{cp}}{f'_c} = \frac{SA_f}{SA_i} = \frac{SA_N{*}V_N + SA_P{*}V_P}{SA_N} \quad \textbf{(17)}$$

where f'_{cp} is the compressive strength of concrete containing plastic aggregate, f_c' is the compressive strength of control concrete, SA_f is the final surface area, SA_i is the initial surface area, SA_N is the surface area of natural aggregate, SA_P is the surface area of PA, V_N is the volume ratio of natural aggregate, and V_P is the volume ratio of PA. Concerning the splitting tensile strength loss, it was assumed that the tensile strength loss due to plastic aggregate addition was similar to that of compressive strength loss, and on this base, the splitting tensile strength ratio is given by

$$\frac{f_{spp}}{f_{sp}} = \frac{SA_f}{SA_i} = \frac{SA_N{*}V_N + SA_P{*}V_P}{SA_N} \quad \textbf{(18)}$$

where f_{spp} is the splitting tensile strength of concrete containing PA, and f_{sp} is the splitting tensile strength of control concrete. However, there may be a difference between the compressive strength loss and the splitting tensile strength loss. Also, the source of the difference could be related to the effect of the PA particle's smoothness and hydrophobicity on the bond between the cement paste and PA, discussed later. In order to work on the proposed surface area model, the following must be given:

(a) the grading of natural and plastic aggregates obtained from sieve analysis,

(b) the test data on specific gravity and bulk density of the two aggregates, and

(c) the thickness of flaky aggregate.

It should be noted that necessary test data on aggregate properties to be used for calculating total surface area were not given by some authors. These experiments were omitted in comparing the test and predicted property in question. However, a limited assumption related to the plastic thickness was made.

4.VALIDITY OF THE PROPOSED MODEL

It is important herein to check the accuracy of the three predictions, and for this purpose, test data from published literature were utilized. A comparison with test data will indicate the accuracy of the proposed model

4.1. Fresh Density

First, there are limited occasions to compare the predictions of fresh concrete density with the test one measured by some researchers because few works on concrete containing PA attempted to measure fresh density. Secondly, most works contain unnecessary data that lead to work on the surface area model because of missing information about the grading of natural and plastic aggregates used and/or information on the specific gravity and bulk density of both aggregates. However, an attempt was made to collect those works containing the necessary data to check the model's accuracy when applied to the density of fresh concrete. Based on test data from Rahmani et al. [4], the fine and PET aggregate particle numbers were calculated using Eq. (7) and tabulated in Table 1, also shows the results of calculated fresh density using Eq. (16) accompanying the test, from which an accurate prediction of mean test/calculated value was equal to 1.004 Da Silva et al. [18] worked on cement mortar of sand partially replaced with two types of plastic aggregates: shredded PET particles and heat-treated pellets. The necessary calculations were followed to obtain the number of natural and plastic aggregate particles and fresh density. The calculation results and the test density measured are given in Table 1. It can be found that the quality of predictions, when applied on the mortar of fine aggregate replaced with PF or PP aggregate, was not good compared to concrete. The test/calculated ratio of fresh density was equal to 1.089, higher than that obtained for the case of concrete tested by Rahmani et al. [4]. As an average, the analysis results showed that the test/calculated ratio of fresh density was 1.046, which is reasonably accurate.

Table 1 Measured and calculated fresh concrete ratio

Reference	Number of particles (in m³)		Calculated density ratio	Measured density ratio	Test / calculated density ratio
	N_s	N_p			
Rahmani et al. [4]	1.21*10^8	1.78*10^8	0.989	0.989	1.000
			0.979	0.982	1.003
			0.968	0.972	1.004
			0.988	0.993	1.005
			0.976	0.981	1.005
			0.963	0.968	1.005
Mean					1.004
Da Silva et al. [18]	6.76*10^8	96955480	0.941	0.983	1.045
			0.884	0.957	1.0833
			0.830	0.940	1.132
		31544977	0.947	0.989	1.044
			0.895	0.970	1.084
			0.846	0.966	1.142
Mean					1.089

4.2. *Compressive and Splitting Tensile Strengths*

In this section, the residual compressive and splitting tensile strengths of concrete due to fine aggregate replacement with PA were calculated. Eq. (17) and 18 were used to predict the two properties based on the data input from previous works which all shown in Table 2 that studied different types of PA in their concrete mixes. Table 2 shows the results of the calculated number of particles, the total surface area, and the predicted compressive and splitting tensile strengths besides the test values. Figs. (2, 3) show the test and calculated compressive and splitting tensile strengths based on data on high high-strength concrete and lightweight concrete, respectively. The data given in Table 2 are for concrete mix tested at the age of 28 days. Below, the results of the predictions are discussed in some detail.

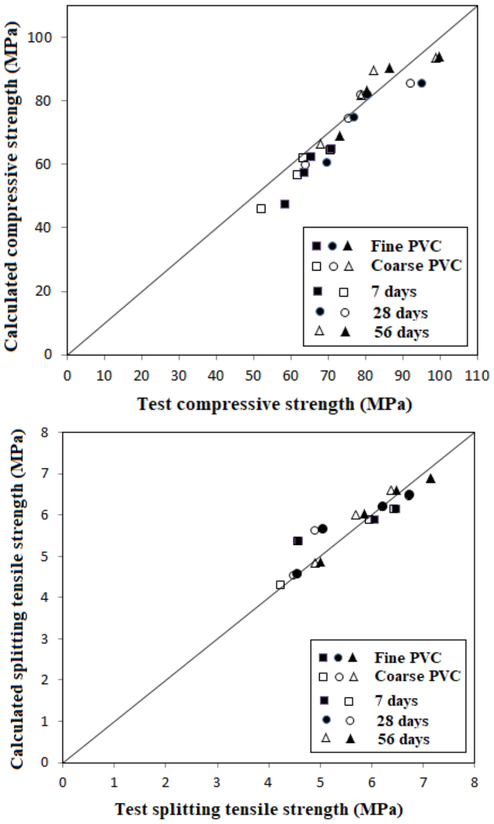


Fig.2 Test and Calculated Strength Mohammed and Mohammed (2020).

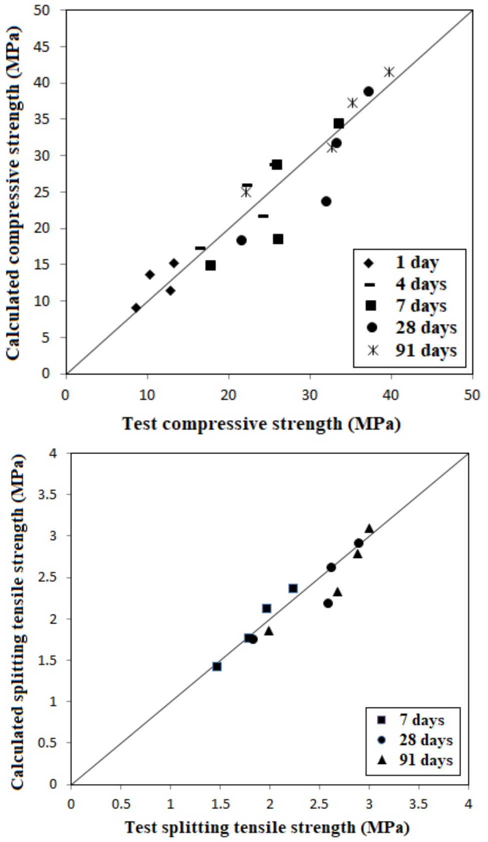


Fig.3 Test and calculated strength Kou et al. (2009).

4.3. Normal Strength Concrete

Rahmani et al. [4] presented no information for the thickness of PET particles, which was assumed to be 0.2 mm, as an average, based on the visual observation of the PET picture given. For the case of normal strength mixes, the results indicated that the mean test/calculated compressive strength ratio was equal to 1.02 (only a 2% error), indicating the accuracy of the proposed model when applied to concrete containing PET aggregate tested by Rahmani et al. [4]. In contrast, the predictions of splitting tensile strength were relatively not good since the test/calculated tensile strength ratio was 0.923; accordingly, the predictions overestimated test data by 7.7%. Since there is no information about the thickness of PET particles given by Saikia and de Brito [10], it was assumed to be 0.2 mm as an average. It can be observed that the predicted splitting tensile strength was quite close to that measured by Saikia and de Brito [10] for a mixture containing PP aggregate. However, the test data for the mix containing flaky PET aggregate was appreciably overestimated. The results indicated that the mean test/calculated compressive strength ratio was equal to 0.739 and 0.913 for a concrete mix containing PET and PP aggregate, respectively. Accordingly, the predicted model underestimated the compressive strength loss because of neglecting the effect of plastic-hardened cement paste bond deficiency. It can be noted that this effect was more important for PET aggregate because of the particle's flaky nature as compared with PP aggregate particles. For concrete tested at the age of 7 days, the mean test/calculated compressive strength ratio was found to be 0.834 and was found to be 0.77 for concrete tested at 91 days. The results presented in Table 2 indicate that the mean test/calculated splitting tensile strength ratio was equal to 0.778 and 1.003 for a concrete mix containing PET and PP aggregate, respectively. Accordingly, the predicted model underestimated the splitting tensile strength loss for concrete with PET aggregate. Consequently, there was a need to account for the effect of aggregate plastic-hardened cement paste bond deficiency to obtain a more accurate prediction. The results of data analysis indicated that the mean test/calculated compressive strength ratio was equal to 0.967 when applied to data by Mohammed et al. [2], accompanying the model non-safety since the calculated strength ratio overestimated the test ratio. According to the obtained results, the test/calculated splitting tensile strength ratio was 0.949; also, the model predictions overestimated the test ratio. Therefore, there was a similarity between using PVC aggregate and PET aggregate in concrete. The aggregate plastic-hardened cement paste bond deficiency was another parameter governing the strength loss. The bond deficiency was mainly caused by the hydrophobicity of plastic particles embedded in concrete. Based on data presented by Ghernouti et al. [19], the results indicated that the mean test/calculated compressive strength ratio was equal to 0.925. This ratio was relatively high compared to concrete containing plastic flake particles. Therefore, the effect of plastic aggregate-hardened cement paste bond deficiency was lower in heat-treated plastic pellets than that of flake PA.

4.4.Mortar

Da Silva et al.'s [18] results indicated that the mean test/calculated compressive strength ratio was equal to 0.716 and 0.948 for concrete with PF and PP, respectively, indicating that the model prediction overestimated the test strength ratio. It can be noted that the predictions had more overestimation for the case of PF aggregate supporting our conclusion about the bond deficiency because the hydrophobicity of the plastic particle was higher when the plastic flakes (PF) were used in concrete, as compared with the plastic pellets (PP).

4.5. High Strength Concrete

The results presented in Table 2 indicate that the mean test/calculated compressive strength tested by Mohammed and Mohammed [8] was equal to 1.06 and 1.022 for concrete with fine PVC and coarse PVC aggregates, respectively, tested at the age of 28 days. A different prediction can be noted compared to the previous cases in which the model underestimated the test data. Therefore, the nature of the bond between hardened cement paste and PVC particle differed, and the transition zone was relatively strong. This behavior was caused by using a lower water/binder ratio that reduced the action of hydrophobicity of plastic embedded in cement paste and also caused by using silica fume that improved the interfacial bond between the plastic particle and cement paste. However, further investigation is required to learn more about these two actions. Fig. 2 shows the calculated and tested compressive strength and the splitting tensile strength at different ages. When the model prediction was applied on specimens tested at seven days, the ratio of the test/predicted compressive strength ratio was 1.112 and 1.076 for concrete mix with fine PVC aggregate and coarse PVC aggregate, respectively, and was equal to 1.012 and 0.989, respectively, for concrete tested at the age of 56 days. The model prediction was fairly accurate when applied to a high-strength concrete mix containing PVC aggregate. The nature of prediction was quite good when applied to the splitting tension. The test/calculated tensile strength was equal to 0.974, 0.979, and 1.004 for concrete containing fine PVC aggregate tested at 7, 28, and 56 days, respectively. For the mix with coarse PVC aggregate, the above values were 0.966, 0.969, and 0.991, respectively. A better prediction was found with increasing the concrete age, possibly due to the plastic aggregate-cement paste bond improvement because of the silica fume used with increasing age. Based on Al-Hadithi and Alani's [6] tests, the analysis results indicated that the mean test/calculated compressive strength ratio was relatively low and equal to 0.642. Accordingly, the prediction well overestimated the compressive strength loss. In contrast, the prediction slightly overestimated the splitting tensile strength since the ratio was equal to 0.956. It should be noted that for specimens tested at the age of 7, 56, and 91 days the test/calculated compressive strength ratio was 0.855, 0.86, and 0.879, respectively. As shown in Table 2, the test/calculated splitting tensile strength ratio was 0.938, 0.991, and 0.991 for the specimens tested at 7, 56, and 91 days, respectively, indicating an increase in the model prediction accuracy with increasing the age of the concrete tested. This behavior could be attributed to the action of silica fume used by Al-Hadithi and Alani [6] with increasing the concrete age. The action of SF also appeared in data given by Jafr [20], in which the nature of prediction was better for mixes containing SF, as shown in Table 2. For the mixes containing pellet PA, the predicted compressive strength was better since the mean test/calculated ratio was 0.964; however, not good for the mixes with IM and PET aggregate (the mean test/calculated ratio was 0.85 and 0.895, respectively) mainly because these mixes contained high ratio of flaky particles.

4.6.Lightweight Concrete

Fig. 3 shows the calculated and tested compressive strength and splitting tensile strength at different ages tested by Kou et al. [7]. The results indicated that the mean test/calculated compressive strength ratio was equal to 1.129 for concrete containing PVC aggregate tested at 28 days. The predictions differed from those discussed in other cases in which the model predictions overestimated the test data since the predicted strength loss was lower than that of test one. In contrast, when the predicted model was applied to the specimens tested at 7 days and 56 days, the ratio of the test/predicted compressive strength ratio was 0.917 and 0.96, respectively. The splitting tensile strength prediction results showed that the mean tested/calculated ratio was equal to 1.053 for the concrete samples tested at 28 days. For the specimens tested at the age of 7 and 56 days, the ratio was 0.977 and 1.056, respectively. As an average, the tested/calculated compressive strength ratio was equal to 1.003, and the splitting tensile strength was equal to 1.029. Consequently, there was no need to use the bond deficiency coefficient (to be done later) for the case of lightweight concrete containing PVC aggregate based on the results of Kou et al. [7]. This behavior may be firstly because the weak point in the lightweight concrete mix tested was the coarse aggregate particle causing final failure, not the interfacial bond between the plastic aggregate and cement paste. Secondly, the PVC aggregate used by Kou et al. [7] was thick and tended to be pellet particles having different action in concrete, as compared with that of the plastic flakes.

4.7.Self-Compacting Concrete

The results indicated that the mean tested/calculated compressive strength ratio was equal to 0.962, 0.834, 0.834, and 0.908. The tested/calculated splitting tensile strength was equal to 0.894, 0.823, 0.899, and 0.925 for concrete with PVC, pellet (PEL), irregular mixed (IM), and PET aggregates, respectively. These ratios are less than unity, identical to most types of concrete previously mentioned in this study. So, the effect of bond deficiency was also available for the case of self-compacting concrete based on the test data given by Abdulqadir [21].

5.BOND DEFICIENCY PARAMETER (D_B) AND RESEARCH NEED

Since for concrete mixes, except for high-strength and lightweight ones, the mean tested/calculated value was lower than unity, there must be an additional parameter to account for more strength loss. This parameter is related to the plastic aggregate particle-cement paste bond deficiency, mainly because the plastic particle hydrophobicity embedded in the cement paste can create a weak transition zone. In this study, this parameter was assessed. Herein, this parameter is called bond deficiency and termed D_b. The bond deficiency of the plastic aggregate particle could be improved by the surface treatments of the plastic and rubber aggregate. Several attempts were made by several researchers such as [22-27], to investigate the effect of the plastic surface treatment aimed to improve the plastic aggregate-cement paste bond to control the strength loss. According to tests by Abu-Saleem et al. [22], the interfacial transition zone between the plastic surface and cement paste was improved due to the PET plastic surface treatment using microwave radiation pre-treatment (MRP), leading to an improvement in the compressive strength, splitting tensile strength, flexural strength, and the concrete modulus of elasticity. As a mixed plastic (PET+HDPE+PP 5% each) was treated and used in concrete, no improvement was observed. This evidence supports the authors' conclusion that the plastic particle's shape and size affected the concrete residual properties. Therefore, to assess D_b utilizing the MRP procedure, tests were required on concrete containing different PAs, with or without surface treatment, to enhance the interfacial plastic aggregate-cement paste bond. Measuring the residual property of the concrete containing PA with or without surface treatment could be done, and the difference led to the experimental assessment of the D_b parameter. Another way to accurately assess the value of the D_b parameter was by testing concrete containing PA with or without mineral admixtures, such as fly ash, silica fume, and metakaolin. As stated before, silica fume enhanced the PA-cement paste bond. Therefore, using mineral admixture by enhancing the interfacial bond enhanced the property of the concrete in question. The difference between the two measurements (with or without mineral admixture) led to assessing the D_b parameter. Considering D_b, the final form of the residual compressive and splitting tensile strength equations are

$$\frac{f'_{cp}}{f'_c} = D_b \frac{SA_N * V_N + SA_P * V_P}{SA_N} \qquad \textbf{(19)}$$

$$\frac{f_{spp}}{f_{sp}} = D_b \frac{SA_N * V_N + SA_P * V_P}{SA_N} \qquad \textbf{(20)}$$

In this study, the D_b parameter was approximately assessed for the concrete compressive strength and splitting tensile strength utilizing those test data on mixes with and without SF. These data were given by Jafr [20] for concrete mixes containing four different PAs given in Table 2 tested in compression. In contrast, for the case of the splitting tensile strength, test data were related to the PVC aggregate (tests by Mohammed et al. [2] and Mohammed and Mohammed [8]). As compressive strength was regarded, for mixes with PVC and pellet PA, no bond deficiency was required, while for mixes with IM and PET aggregate, D_b was considered as 1.09 and 1.02, respectively. For mixes with PVC aggregate tested for splitting tensile strength, D_b could be considered as 1.03. Indeed, further tests are required to better assess the role of the PA-cement paste bond improvement using different treatments, which led to a better assessment of the D_b parameter.

6. CONCLUSION

From this study, the following conclusions are made:

1- Experimental tests by previous researchers showed that the shape and size of plastic aggregate particles influenced the fresh density, compressive strength, and splitting tensile strength of concrete. Consequently, to obtain an accurate prediction of the residual properties of concrete modified with plastic aggregate, the effects of the particle's shape and size should be considered when regression analysis was performed on the collected test data.

2- Considering aggregate particle size and shape effects, calculating the total surface area of natural and plastic aggregates was possible. The authors attempted to assess accurately the properties of the fresh density, compressive strength, and splitting tensile strength of recycled concrete containing different plastic aggregates. The accuracy of the model prediction increased with the curing age of the concrete. Better predictions were obtained for concrete containing plastic pellet aggregate as compared with that containing plastic flakes. The non-accuracy of the prediction was attributed to the plastic particle-cement paste bond deficiency.

3- In contrast to the case of conventional concrete, the model prediction was accurate for the case of high-strength and lightweight concretes. Using a low water-to-binder ratio and the existence of silica fume in high-strength concrete enhanced the plastic aggregate-hardened cement paste interfacial bond leading to an accurate prediction. The bond deficiency parameter (Db) was assessed for the case of normal-strength concrete to obtain more accurate results.

4- Using the total surface area of aggregate had a feasibility to be applied to predict different properties of concrete mixes modified with different recycled aggregates; however, there is a need for further investigation.

Table 2 Test/Calculated Compressive Strength and Splitting Tensile Strength

Type of concrete	References	Type of PA	PA (%)	Natural Agg.		Plastic Agg.		$\frac{f'_{cp}}{f'_c}$			$\frac{f_{spp}}{f_{sp}}$		
				N_{FA} x 10^6 (per m^3)	SA_N (m^2/m^3)	N_P x 10^6 (per m^3)	SA_P (m^2/m^3)	Calculated	Test	Test / Calculated	Calculated	Test	Test / Calculated
Normal strength	Rahmani et al. [4]	PET	5	128	6276	178	4190	0.983	0.964	0.981	-	-	-
			10					0.967	0.915	0.947			
			15					0.95	0.844	0.888			
			5					0.983	1.09	1.11			
			10					0.967	0.971	1.01			
			15					0.95	0.937	0.986			
			5					0.983	1.09	1.11	0.983	0.98	0.996
			10					0.967	1.03	1.06	0.967	0.927	0.959
			15					0.95	0.949	1.0	0.95	0.851	0.896
			5					0.983	1.12	1.14	0.983	0.95	0.966
			10					0.967	1.01	1.04	0.967	0.862	0.892
			15					0.95	0.915	0.96	0.95	0.785	0.826
	Saikia and de Brito [10]	PET	5	103	5180	310	3350	0.982	0.838	0.854	0.982	0.88	0.896
			10					0.965	0.715	0.741	0.965	0.75	0.778
			15					0.95	0.588	0.621	0.947	0.624	0.659
		PP	5			26.15	1137	0.961	0.878	0.914	0.961	0.921	0.959
			10					0.922	0.856	0.928	0.922	0.972	1.054
			15					0.883	0.792	0.897	0.883	0.88	0.996
	Mohammed et al. [2]	PVC	5	62.65	5048	64.46	1372	0.964	0.955	0.991	0.964	0.895	0.928
			15					0.891	0.912	1.024	0.891	0.986	1.107
			30					0.782	0.774	0.99	0.782	0.675	0.864
			45					0.672	0.58	0.862	0.672	0.621	0.924
			65					0.527	0.472	0.896	0.527	0.481	0.914
			85					0.381	0.395	1.037	0.381	0.365	0.957
	Ghernouti et al. [19]	PP	10	152	5641	45.67	1426	0.925	0.893	0.965	-	-	-
			20					0.851	0.746	0.877			
			30					0.776	0.71	0.915			
			40					0.701	0.66	0.942			
Mortar	Da Silva et al. [18]	PET	5	676	10545	96.96	1316	0.956	0.962	1.006	-	-	-
			10					0.912	0.516	0.566			
			15					0.869	0.500	0.576			
		PP	5			31.54	1192	0.956	0.897	0.938	-	-	-
			10					0.911	0.891	0.978			
			15					0.869	0.804	0.928			
High strength	Mohammed and Mohammed [8]	Fine PVC	5	136	7407	756	1446	0.96	1.06	1.104	0.96	0.996	1.037
			10					0.92	0.897	0.975	0.92	0.919	0.999
			20					0.839	0.856	1.02	0.839	0.839	0.889
			40					0.678	0.774	1.142	0.678	0.678	0.993
		Coarse PVC	5			90.31	1341	0.959	1.026	1.07	0.959	0.991	1.033
			10					0.918	0.877	0.955	0.918	0.914	0.996
			20					0.836	0.839	1.003	0.836	0.723	0.865
			40					0.672	0.712	1.059	0.672	0.661	0.983
	Al-Hadithi and Alani [6]	PET	5	152	6935	164	3017	0.986	0.675	0.684	0.986	1.036	1.051
			15					0.972	0.636	0.655	0.972	0.884	0.909
			30					0.958	0.563	0.587	0.958	0.868	0.907
	Jafr [20]	PVC	5	127	7272	212	2410	0.967	0.985	1.019	-	-	-
			10					0.933	0.956	1.024			
			15					0.900	0.886	0.985			
			20					0.866	0.834	0.963			
			5					0.967	0.891*	0.922			
			10					0.933	0.830*	0.889			
			15					0.900	0.81*	0.900			
			20					0.866	0.738*	0.852			
		PP	5			15.55	992	0.957	0.973	1.017			
			10					0.914	0.895	0.980			
			15					0.870	0.834	0.958			
			20					0.827	0.766	0.926			
			5					0.957	0.924*	0.966			
			10					0.914	0.896*	0.981			
			15					0.870	0.807*	0.927			
			20					0.827	0.788*	0.953			
		IM	5			15.33	858	0.956	0.930	0.973			
			10					0.912	0.718	0.787			
			15					0.868	0.695	0.800			
			20					0.824	0.580	0.704			
			5					0.956	0.914*	0.956			
			10					0.912	0.883*	0.968			
			15					0.868	0.712*	0.821			
			20					0.824	0.654*	0.793			
		PET	5			55.62	1475	0.960	0.898	0.935			
			10					0.920	0.847	0.920			
			15					0.880	0.731	0.830			
			20					0.841	0.721	0.858			
			5					0.960	0.942*	0.981			
			10					0.920	0.840*	0.913			
			15					0.880	0.775*	0.880			
			20					0.841	0.707*	0.841			
Lightweight	Kou et al. [7]	PVC	5	830	12350	10	638	0.953	0.909	0.955	0.953	0.944	0.991
			15					0.858	0.895	1.043	0.858	0.856	0.998
			30					0.716	0.961	1.343	0.716	0.843	1.178
			45					0.573	0.674	1.176	0.573	0.598	1.043
Self-compacting	Abdulqadir [21]	PVC	2.5	150	6925	173	1532	0.982	0.930	0.948	0.982	0.756	0.771
			5					0.961	0.929	0.966	0.961	0.911	0.948
			7.5					0.942	0.925	0.982	0.942	0.898	0.954
			10					0.922	0.878	0.952	0.922	0.833	0.903
		PP	2.5			13.18	847	0.978	0.856	0.875	0.978	0.817	0.836
			5					0.956	0.791	0.828	0.956	0.724	0.757
			7.5					0.934	0.772	0.826	0.934	0.778	0.833
			10					0.912	0.729	0.799	0.912	0.791	0.867
		IM	2.5			16.17	914	0.978	0.926	0.947	0.978	0.887	0.907
			5					0.957	0.844	0.882	0.957	0.837	0.875
			7.5					0.935	0.730	0.781	0.935	0.820	0.877
			10					0.913	0.664	0.727	0.913	0.855	0.936
		PET	2.5			79.23	2135	0.983	0.932	0.949	0.983	0.947	0.964
			5					0.965	0.897	0.929	0.965	0.907	0.939
			7.5					0.948	0.832	0.878	0.948	0.872	0.919
			10					0.931	0.815	0.875	0.931	0.816	0.877

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