Implementation and validation of Dewar's particle packing model for recycled concrete aggregates

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ABSTRACT

This paper validates Dewar's particle packing modelling (PPM) theory for implementing both fine and coarse recycled concrete aggregates (RCAs) from using aggregates with multi-size classes (0/1, 0/4, 2/8, 0/8, 8/20, 0/20). The voids ratios of aggregate mixtures were evaluated experimentally and compared with the predictions. The model shows high predicting accuracy for implementing coarse RCA. A size ratio adjustment factor might be necessary to calibrate the model for implementing fine RCA and all-in fractions (0/8, 0/20). A practical method for evaluating this factor is proposed. The powder within the investigated aggregates has limited impact on the estimation of the voids ratio of aggregate mixtures. However, the powder fraction shall have an effect on the final mix design as well as on the fresh and hardened concrete properties.

KEYWORDS: interaction diagrams, particle interference, Particle packing modelling (PPM), Natural and recycled concrete aggregate (NA&RCA), Single-sized, multi-sized and all-in aggregates.

1. Introduction

Concrete recycling has gained much attention since last centuries, especially after the Second World War. The rapid growth of population and economy has accelerated the industrialization and urbanization [1] and resulted in huge amounts of construction & demolition waste (C&DW) [2,3]. Moreover, the yearly concrete production is still

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1 increasing since concrete will not be replaceable in the coming years. It can be expected that the annual produced
2 C&DW will significantly increase in the future. Although recycled aggregate (RA) from C&DW [4–6] has been used
3 as landfilling or road construction material, upscaled application of RA for producing structural concrete is more
4 favoured [7–10], regardless if it is fine or coarse RA. Furthermore, the scarcity of natural resources has forced the
5 concrete industry to use secondary raw materials due to the increased price of natural materials. Life cycle assessment
6 (LCA) has been adopted by many researchers in order to evaluate and to compare environmental benefits related to
7 the use of RAs or recycled concrete aggregates (RCAs) in concrete production [11–13]. For concrete mixes with
8 different aggregate types (NA and RCA), the cement was not the deciding contributor to some impact categories [12].
9 Clear benefits could be identified from utilizing RAs in concrete in terms of water reduction and minimization of
10 natural mineral resource depletion [13]. Using RAs for concrete production is therefore an ecological and economic
11 strategy.

12 In the RA family, including RCA, recycled ceramic aggregate and mixed recycled aggregate, the RCA is found to be
13 more suitable for producing structural concrete because of its favourable characteristics in comparison to those of
14 recycled ceramic aggregate and mixed recycled aggregate [7]. Nevertheless, the RCA has a decisive influence on the
15 concrete performances due to the impurities and residual mortar content and this influence increases generally as the
16 replacement percentage of RCA increases [7,10,14–16]. So far many studies have been carried out for concrete with
17 coarse RCA [17–26]. Some countries have established standards or quality certificates for the use of coarse RCA with
18 some limitations [27]. On the contrary, the fine RCA has been less studied [28] and is normally not recommended or
19 even banned to use in concrete production [27]. However, based on the findings from some available studies [28,29],
20 concrete with fine RCA could satisfy the requirements for structural concrete. From 2004 onwards, fine RCA has
21 gained more attention and is provoked to be used in concrete [28,30]. Nevertheless, mitigations against the influence
22 of RCAs on concrete performances should be taken for utilising the material's value. Among others, particle packing
23 modelling (PPM) has been considered as a method to mitigate the drawbacks of RCA on concrete performances
24 through the optimization of the concrete mixtures.

25 Two categories of particle packing models for proportioning concrete mixtures could be distinguished [1,31,32],
26 namely continuous models and discrete models. The former proportions concrete mixtures to match an “ideal” grading
27 curve based on the particle size distribution of its ingredients [31], while the latter does take also other physical
28 properties into account (e.g., voids ratio, compaction energy, etc.), providing further information for estimating the

concrete performances (mechanical properties, durability, etc.). So far, there are many computer-based mix constituent proportioning tools available based on different PPM theories [31,32], which facilitate the concrete mix design process and make it possible to optimize concrete mixtures (minimize the paste content, maximize the RCA content, design concrete with target performances, etc.) in the design phase with the embodied performance models. Many studies [33,34] have been performed for the packing of natural aggregates (NAs) or concrete mixtures with pure NAs both theoretically and experimentally. The results from those researchers asserted the applicability of PPM on predicting the packing density of aggregate mixtures with the use of NAs (e.g., sand, crushed limestone, gravel), despite the fact that calibrations might be required [35–37]. Studies on the PPM of concrete mixtures with RCAs are limited. Pradhan et al. [1] applied the Compressible Packing Model (CPM) [38] to design recycled aggregate concrete (RAC) by replacing coarse NA with coarse RCA. The theoretical packing density for both NA concrete and RAC compositions did not reflect good correlation with the experimental ones when the compaction index 4.5 for dry rodding procedure was adopted. Instead, a higher compaction factor (i.e., 6.5) was required for calibrating the packing density for the concrete mixtures. The reason behind this is however not underpinned by Pradhan et al., [1]. Furthermore, only single-sized coarse RCA were used in their study, which does not cover all the possible aggregates mixtures with RCAs. As shown by Pradhan et al., [1], in comparison to the design method according to IS 10262 (2009), the PPM mix proportioning did not significantly improve the workability of the fresh concrete for both natural aggregate concrete (NAC) and RAC, but it did have positive effect in improving the tensile strength and enhancing the modulus of elasticity of both NAC and RAC. Huang et al., [39] studied the compressive strength of RAC mixtures in relation to the packing density of individual aggregates and the whole mixtures and concluded that the adoption of packing density of concrete mixtures can limit the RAC strength fluctuations and minimise the influence of RCAs obtained from various sources with variable qualities.

Designing low-binder concrete mixtures with satisfied performances can be obtained by optimizing the concrete solid system [1,40]. LCA carried out by Pradhan et al., [12] revealed that concrete designed by following the PPM mix design approach shows higher impacts on lowering environmental burden for the investigated categories (abiotic depletion, abiotic depletion due to fossil fuels, global warming potential, depletion of ozone layer, formation of tropospheric ozone photochemical oxidants, acidification potential, and eutrophication potential impact categories) in comparison to the concrete proportioned by following the IS 10262 (2009) approach, in case identical aggregate types (NA or RCA) were used. This is attributed to the fact that less cement is required for concrete mixes designed by the

1 PPM approach. Synergistic effect from lowering the cement and replacing NA with RCA was noticed in improving
2 the sustainability of concrete.

3 Ecological and economic benefits from designing RAC by a PPM approach can be expected. However, the
4 applicability of PPM theory with respect to the implementation of RCAs is not clearly understood, especially for the
5 use of fine RCA and all-in RCA fraction. Liu et al., [30] determined the packing density of aggregate mixtures with
6 fine RCA and compared with the predictions based on the packing model from Dewar [41]. In their study, the content
7 of fine particles (powder content) found within all-in RCA was considerably higher than that in natural sand and the
8 filling effect of this powder with respect to the packing density is still not clear. Although it seems RAC mixtures can
9 be proportioned based on PPM [1,12,39,42], the systematic validation of the PPM theory for the interaction between
10 NA&RCA and RCA&RCA is still blank, which is the aim of the present study.

11 Dewar's Model [41] was selected in this study because it is an efficient model with limited input parameters. The
12 basic inputs for the modelling are the estimated log mean size and the voids ratio of the materials. With this information
13 the voids ratio of the combined mixes in relation to the fine fraction value n (replacing level of finer material to the
14 coarser material by volume) can be estimated [28,40,41]. Unlike the CPM, the ambiguity regarding the energy level
15 can be avoided from applying Dewar's Model since no compaction energy is required for estimating the voids ratio
16 of the material in uncompacted state. Particles with high surface friction or irregular shape can have higher voids ratio
17 value in the uncompacted state as compared with smooth round materials. The particle shape and particle texture,
18 amongst others, are partially and indirectly considered by the loose bulk density value and voids ratio value of the
19 material, regardless if it is NA or RCA, overcoming the limitations from extending the theory to irregular particle
20 shape as identified in the 3-parameter model [43]. Water demand of concrete in function of the binder content can be
21 estimated from the model and can further be used to predict concrete properties [44–46].

22 The packing theory from Dewar assumes that a graded material can be represented by a single-sized material having
23 the same voids ratio and mean size as the graded material and that the sequence of combining fractions is arranged
24 from the finest material to the coarser material. The extension from single-sized fraction to graded fraction (regardless
25 of NA or RCA) based on Dewar's assumption, however, could jeopardize the estimation of the fraction mean sizes
26 and further affect the size ratio r (ratio of the smaller mean size to the bigger mean size of the fractions of an aggregate
27 mixture) [41]. Moreover, properties as particle shape (although partially considered in the estimation of voids ratio),
28 density, etc. differ for RCAs and NAs [30] and it may affect the size ratio of aggregate mixtures. An adjustment factor

1 F for NA was applied on size ratio r to improve the predicting accuracy of Dewar's model.

2 The predicted voids ratio diagram of combined fractions based on Dewar's model is featured by six change points and
3 a linear relation between these points. It starts from the binary packing of two materials and can be extended to multi-
4 materials packing. The voids ratio of powder (<0.063 mm) is estimated from the water demand of paste at the Vicat
5 Standard Consistence by assuming that the water and air will fill the voids of the powder (wet packing). In combination
6 with the use of superplasticizers, dispersion of the powder particles is enhanced. On the contrary, the voids ratio of
7 aggregate is estimated based on the loose bulk density and specific density (dry packing). To bridge the packing of
8 powder (wet packing) and of aggregate (dry packing), an empirical adjustment factor J is applied on the change points
9 of the mortar solid system (powder as the finer material and fine aggregate as the coarser material). As a result, the
10 volume of each component within concrete mixtures can be estimated mathematically.

11 Concrete mixture parameters/properties (e.g., water/cement ratio, water/binder ratio, compressive strength, etc.) can
12 be further calculated and predicted, providing information for selecting appropriate concrete mixtures [1,40,41]. For
13 example, by optimizing of the voids ratio, concrete mixtures with a target consistency can be formulated with less
14 paste [40]. Different NAs (e.g., crushed limestone, gravel) and the commonly used powders in concrete (e.g., cement,
15 fly ash, slag, limestone fillers) were used with different particle packing models [34,40,41,47], asserting the
16 applicability of PPM theory for those materials but not yet for RCAs. A sensitivity analysis was carried out by Liu et
17 al., [48] of the voids ratio and fine fraction value of combined fractions to the basic parameters based on Dewar's
18 model. It shows that the material properties and the customized parameters within the model have impact on the voids
19 ratio of the mixes in different degree and the impact differs for different size ratios.

20 Dewar [41] believed that particles will be interfered by added new particles, creating a higher voids ratio. The finer
21 fraction as well as the coarser fraction will get disturbed when the finer fraction is filled in the voids of the coarser
22 fraction and the interference will increase with the increase in size ratio. Special care or treatment is required with
23 respect to the practical packing of the particles [41]:

- 24 1) The packing starts strictly from the finer to the coarser step by step, extending firstly binary packing to multi-
25 components packing. Higher resultant voids ratio occurs if the sequence is reversed (except for materials
26 which have close size, these can be pre-combined);
- 27 2) Material which has a gap in the grading should be considered as two separate materials. Strictly combine the
28 finest materials first to the next coarser fraction until all the fractions are included;

- 3) When a fraction is to be combined with a fraction which has a wide grading curve (size class interference, e.g., fraction 0/20 with fraction 8/20), the wide-graded fraction should be split into its components (one finer and one coarser, e.g., split 0/20 into 0/8 and 8/20). Combine the finest materials first to the next coarser fraction until all the fractions are included (except for materials which have close size, these can be pre-combined).

The presented work aims to find a methodology to design sustainable and economic RAC mixtures with a simple and effective particle packing model. A good characterization of the constituents and models (packing model, strength model, consistency model, durability models) can lead to a better global prediction and evaluation of the concrete towards water demand, strength, consistency and durability. It is feasible and convenient to use the model to predict changes in performance based on changes in concrete constituents and their dosage (which is a typical situation occurring in practice where concrete mixes should be regularly adapted based on changing incoming concrete ingredients). The paper focuses therefore on the first steps which include a validation of Dewar's packing model for the implementation of RCAs from the (binary) packing of aggregates. The novelty of the work relates to the implementation of fine RCA as well as all-in aggregate in the packing density theory (no studies have been found so far) and to the formulation of a practical guideline to calibrate the PPM theory from Dewar.

The work includes an evaluation of the experimental voids ratios of aggregate mixtures and a comparison with the predicted ones from Dewar's model. The following issues will be addressed:

- 1) Interaction of NA&NA together with NA&RCA and RCA&RCA;
- 2) Interaction tests for different size ratios of the combined fractions: ~ 0.03 , ~ 0.1 , ~ 0.2 , ~ 0.4 , ~ 0.75 , ~ 1.0 ;
- 3) Packing of graded fractions with $D/d > 2$ (d is the lower nominal size and D is the upper nominal size), which are 0/1, 0/4, 2/8, 0/8, 8/20, 0/20 and all-in fractions ($d = 0, D > 4 \text{ mm}$), which are 0/8, 0/20;
- 4) Influence of powder content ($< 0.063 \text{ mm}$) in the aggregates on the packing density of aggregates and aggregate mixtures;
- 5) Practical guideline to estimate the size ratio adjustment factor F for calibrating the size ratio.

2. Methodology and Experimental program

2.1. Materials

An overview of all the aggregates used in this study is shown in Table 1 and these aggregates can be classified into

three groups, which are fine aggregate ($d = 0 \text{ mm}$, $D \leq 4 \text{ mm}$), coarse aggregate ($d \geq 1 \text{ mm}$, $D > 4 \text{ mm}$) and all-in aggregate ($d = 0 \text{ mm}$, $D > 4 \text{ mm}$). Aggregates with an identical fraction, but from a different source or batch are indicated by the letters A, B, C, D. The fraction size and the type of the aggregates are in accordance with the specifications in NBN EN 12620 (2013). All the aggregates used in this study are graded fractions. Sand 0/1 A and Sand 0/1 B are sea sands and Sand 0/4 is a river sand. A two stage crushing process (jaw crusher and impact crusher) was applied to obtain the RCA fractions. RCA 0/4 is a separated fraction by sieve 4 mm (separated in the laboratory) from the RCA 0/8 C and is considered as an individual material.

Table 1. Overview of the materials (FS = Fine sand; CLM = Coarse limestone; ALM = All-in limestone; FRCA = Fine recycled concrete aggregate; ARCA = All-in recycled concrete aggregate; CRCA = Coarse recycled concrete aggregate).

Materials	Type of aggregate	Abbreviation
Sand 0/1 A	Fine NA	FS1
Sand 0/1 B	Fine NA	FS2
Sand 0/4	Fine NA	FS3
Limestone 2/8	Coarse NA	CLM1
Limestone 8/20 A	Coarse NA	CLM2
Limestone 8/20 B	Coarse NA	CLM3
Limestone 8/20 C	Coarse NA	CLM4
Limestone 0/20	All-in NA	ALM
RCA 0/4	Fine RCA	FRCA
RCA 0/8 A	All-in RCA	ARCA1
RCA 0/8 B	All-in RCA	ARCA2
RCA 0/8 C	All-in RCA	ARCA3
RCA 8/20 A	Coarse RCA	CRCA1
RCA 8/20 B	Coarse RCA	CRCA2
RCA 8/20 C	Coarse RCA	CRCA3
RCA 8/20 D	Coarse RCA	CRCA4

RCA 0/20	All-in RCA	ARCA4
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In case of packing of two aggregates with size class interference, aggregate should be split and the components should be characterized (see Section 1). An overview of the split fractions and its components is given in Table 2. Fractions ALM-I and FRCA1-I were the powders separated in the laboratory from respectively ALM and FRCA by sieving at 0.063 mm in order to evaluate the influence of the powder content on the properties of ALM and FRCA and on the packing density of the aggregate mixtures with these fractions. Following the standard procedure for determining the particle densities (NBN EN 1097-6, 2013), the powder content at 0.063 mm should be removed by wet sieving for fine aggregate and the particle smaller than 4 mm should be removed by wet sieving for coarse aggregate with $d > 4$ mm. For the Limestone 2/8, the samples were washed on the sieve with opening 0.063 mm in this study and used as such for determining the particle densities according to NBN EN 1097-6, 2013. Although in the present work powders were sieved at 0.063 mm, authors recognize the importance of the fine particles in the RCA and NA (particles smaller than 0.125 mm or 0.250 mm) in the concrete mix design. Therefore, it could be possible that these particles in the PPM should be allocated to the powder fraction instead of the aggregate fraction.

Table 2. Average weight shares of the split components from the original fractions.

Materials	Components
Limestone 0/20 (ALM)	ALM-I (0/0.063mm, 2.5%), ALM-II-1 (0.063/8mm, 71.3%), ALM-II-2 (0/8mm, 73.8%), ALM-III (8/20mm, 26.2%)
RCA 0/4 (FRCA)	FRCA-I (0/0.063mm, 2.9%), FRCA-II (0.063/4mm, 97.1%)
RCA 0/8 C (ARCA3)	ARCA3-I (0/2mm, 55.9%), ARCA3-II (2/8mm, 44.1%)
RCA 0/20 (ARCA4)	ARCA4-I (0/8mm, 57.0%), ARCA4-II (8/20mm, 43.0%)

Aggregates and powders were characterized and the methods for determining these properties are basically following the standards. At least 3 repetitions (or 5 repetitions for the particle size distribution) were available; only for the determination of the specific density and water demand of the powders, one single measurement was done due to the limited availability of powder fraction.

- Apparent density, oven-dried density, water absorption in 24h of aggregate: NBN EN 1097-6 (2013) with 1 kg

sample;

- Particle size distribution of aggregate: NBN EN 933-1 (2012);
- Loose bulk density of aggregate: NBN EN 1097-3 (1998);
- Specific density (relative density) of powder: NBN EN 1097-7 (2008);
- Water demand of paste at Vicat Standard Consistence: NBN EN 196-3 (2016);
- Particle size distribution of powder: laser diffraction.

2.2. Estimation of the basic inputs for the PPM

The voids ratios of two combined materials (which are the voids ratio of the finer material U_1 and the voids ratio of the coarser material U_0) and the size ratio r (the ratio of the log mean size of finer material d_1 to the log mean size of coarser material d_0) of the combined materials are the basic inputs for predicting the voids ratio of the aggregate mixtures. The prediction of the voids ratio of mixed aggregates is basically a mathematical calculation with material properties and embedded model parameters.

For aggregates, the voids ratio U can be calculated (dry packing) by its relative density RD (which is the ratio of the oven-dried density ρ_{rd} to the density of water ρ_{water} ; ρ_{water} is taken as 1000 kg/m³) and loose bulk density ρ_{LB} (dry packing) by Eq. (1):

$$U = \frac{1000 \times RD}{\rho_{LB}} - 1 = \frac{\rho_{rd}}{\rho_{LB}} - 1 \quad (1)$$

With respect to the powders, specifically ALM-I and FRCA1-I in this study, the voids ratio can be calculated (wet packing) by Eq. (2):

$$U = (RD_p \times SC + a_p)/(100 - a_p) \quad (2)$$

where RD_p is the relative density of the powder; SC is the water demand of the paste from Vicat Standard Consistence test, denoted as a percentage of mass of the powder; and a_p is the air content in percentage in paste, defined as 1.5 by Dewar [41].

The log mean size of the fraction can be estimated according to Dewar [41] from the volumetric particle size distribution curve following Eqs. (3) and (4).

For each single-sized fraction ($D/d \leq 2$):

$$\text{Log}(\text{mean size of sieve fraction}) = \frac{\text{Log}(\text{upper sieve size}) + \text{Log}(\text{lower sieve size})}{2} \quad (3)$$

1 For graded fraction ($D/d > 2$):

$$\text{Log}(\text{mean size}) = \sum [\text{vol. proportion} \times \log(\text{mean size of the sieve fraction})] \quad (4)$$

2 2.3. Voids ratio predicting from Dewar model

3 The voids ratio diagram of the combined aggregates in function of the fine fraction value n (volumetric proportion of
4 finer fraction to the overall volume of the mixture) can be drawn according to Dewar [41] by using several change
5 points (denoted as A to F). These change points are associated with the material properties of the blended fractions
6 and the particular factor m and empirical factors k_{int} and k_p from Table 3. A linear function is assumed between the
7 different change points. The voids ratio U_n and fine fraction n of each change point can be calculated by Eqs. (5-9).

8 Voids ratio of a mixture of finer and coarser fractions:

$$U_n = nU_1'' \quad (5)$$

9 Effective voids ratio of the finer fraction:

$$U_1'' = \frac{(1 + U_1)U_0''}{(1 + U_0'') - (1 + Z)^3} - 1 \quad (6)$$

10 Effective voids ratio of the coarser fraction:

$$U_0'' = (1 + U_0)(1 + mr)^3 - 1 \quad (7)$$

11 With

$$n = \text{fraction of fines in the mixture} = \frac{U_0''}{1 + U_1'' + U_0''} \quad (8)$$

$$r = \text{size ratio of the aggregate mixtures} = d_1/d_0$$

$$m = \text{spacing factor related to the fraction of fines in the mixtures (Table 3)}$$

$$Z = \text{notional width factor} = k_{int} + [(1 + U_0)^{1/3} - 1 - k_{int}]r^{k_p} \quad (9)$$

16 Table 3. Parameters m , k_{int} and k_p for the change points in Dewar Model [41].

Change points	Parameters		
	m	k_{int}	k_p
A ($n=0$)	0	-	-
B	0.3	0.12	0.60
C	0.75	0.06	0.65
D	3	0.015	0.8
E	7.5	0	0.9
F ($n=1$)	∞	-	-

2.4. Experimental voids ratio

The voids ratio of mixed finer and coarser fractions U_{lab} from laboratory experimental test in relation with n (fine fraction value) could be estimated by the theoretical oven-dried density of the mixture ρ_{rd_n} (calculated from Eq. (10) with the oven-dried densities of the finer and coarser fraction (ρ_{rd_1} and ρ_{rd_0} , respectively)) and the experimental loose bulk density of the mixture from Eq. (1).

$$\rho_{rd_n} = n\rho_{rd_1} + (1 - n)\rho_{rd_0} \quad (10)$$

At least three measurements were taken for each mix and the mean value of these measurements was denoted as the experimental voids ratio in this study.

2.5. Interaction tests of binary packing of aggregates

The implementation and validation program for RCAs in this study focuses on the binary packing for the combination of NA&RCA and RCA&RCA, in addition to the validation of NA&NA. For each interaction test (combinations of two materials), the voids ratios were evaluated experimentally at different replacing levels of the fine fraction n ranging from 0 to 1 at an interval of 0.1. The materials used for the systematic interaction test program can be seen in Table 4.

Three types of interaction groups can be classified from the interaction tests (* indicates mixtures with fractions having size class interference and the prediction of these groups were made based on the properties of the components from

the aggregates as mentioned in Section 1):

- NN (interaction tests between NA&NA with the indication of size ratio class): NN0.03, NN0.1, NN0.2, NN*0.2, NN0.4, NN0.75, NN1.0;
- NR (interaction tests between NA&RCA with the indication of size ratio class): NR0.03, NR0.1, NR*0.2, NR0.4, NR0.75, NR1.0;
- RR (interaction tests between RCA&RCA with the indication of size ratio class): RR0.03, RR0.1, RR*0.2, RR*0.4, RR0.75, RR1.0.

Table 4. Overview of the interaction test program: mixture codes and the aggregates used in the test.

Size ratio [-]	NA&NA	NA&RCA	RCA&RCA
~0.03	NN0.03: FS2&CLM2	NR0.03: FS2&CRCA1	RR0.03: FRCA&CRCA2
~0.1	NN0.1: FS2&CLM1	NR0.1: ARCA3&CLM3	RR0.1: ARCA3&CRCA1
~0.2	NN0.2: FS3&CLM1 NN*0.2: ALM&CLM3	NR*0.2: FS2&ARCA2	RR*0.2: ARCA4&CRCA3
~0.4	NN0.4: CLM1&CLM4	NR0.4:ARCA1&CLM1	RR*0.4: ARCA2&ARCA4
~0.75	NN0.75: CLM4&CLM3	NR0.75:CRCA1&CLM2	RR0.75: CRCA1&CRCA2
~1	NN1.0: FS1&FS2	NR1.0: CLM4&CRCA1	RR1.0: CRCA4&CRCA1

* Mixtures with fractions having size class interference.

2.6. Differences of the experimental voids ratios to the predictions

The sum of the squared differences of experimental voids ratios to the predicting ones (called *Diff*) and its average (called $\overline{Diff}$) were calculated by Eqs. (11) and (12) respectively for the evaluation:

$$Diff = \sum R^2 = \sum_{i=1}^{i=N} (U_{lab_i} - U_{Dewar_i})^2 \quad (11)$$

$$\overline{Diff} = \overline{\sum R^2} = \Sigma R^2 / N = \left[\sum_{i=1}^{i=N} (U_{lab_i} - U_{Dewar_i})^2 \right] / N \quad (12)$$

where i is the i^{th} experimental point (corresponding with a certain fine fraction content) from one interaction test; N is the number of the experimental points from different replacement levels (not including the 0% and 100%); U_{lab_i} is the experimental voids ratio as mentioned in Section 2.4 at the i^{th} point; U_{Dewar_i} is the predicted voids ratio by Dewar's model as described in Section 2.3 at the i^{th} point.

2.7. Adjustment factor F for different scenarios

The PPM theory from Dewar can easily predict the voids ratio of an aggregate mixture. However, the accuracy of the prediction relies on the accurate estimation of the basic inputs used in the model. Dewar [41] used an adjustment factor F to correct the size ratio r of NA mixtures (resulting in $F \times r$) since the log mean size and the particle size distribution of a fraction can be inaccurate from the sieving process. Particles which are relatively insensitive by the boundary sieve size from the sieving process may not be accurately discriminated.

There are, however, no clear clues to estimate the adjustment factor F . Dewar [41] made his adjustment for the size ratio simply by trial and error on the basis of observed differences. Liu et al., [30] estimated this factor by fitting experimental voids ratios to the predictions by the Least Square Method (LSM) for some aggregate mixtures with RCAs and NAs. The fitting from Liu et al. [30] improved the predicting accuracy of the model, but it is not practical when it comes to concrete mixture design for engineers. In this study, adjustment factors were estimated from different fitting scenarios by the LSM and the corresponding differences were calculated and compared. An overview of the different fitting scenarios is summarized in Table 5. The voids ratios used for evaluating the fitting scenarios in this study are equally spread along the fine fraction value of the aggregate mixtures between 0 to 1.

Besides analysing the own dataset (in total 9 evaluated experimental points for each interaction group in this study), also the experimental dataset obtained by Dewar [41] was analysed as reference. In the latter case, only available points or the closest available ones that correspond to the fine fraction values were considered to estimate the adjustment factors.

Table 5. Overview of the fitting scenarios for estimating size ratio adjustment factors.

Fitting type	Code	Fitting by the adjustment of size ratio
Global Fitting (GF)	GF	All available experimental points
Single Point Fitting	SPF0.2	Fine fraction value 0.2 point

(SPF)	SPF0.3	Fine fraction value 0.3 point
	SPF0.4	Fine fraction value 0.4 point
	SPF0.5	Fine fraction value 0.5 point
	SPF0.6	Fine fraction value 0.6 point
	SPF0.7	Fine fraction value 0.7 point
	SPF0.8	Fine fraction value 0.8 point
Three Points Fitting	TPF0.3-0.5	Fine fraction value 0.3, 0.4 and 0.5 points
(TPF)	TPF0.4-0.6	Fine fraction value 0.4, 0.5 and 0.6 points
Dewar Fitting (DF)	DF	Adjustment factors applied by Dewar
No Fitting applied (NF)	NF	No adjustments were made

3. Results and discussion

3.1. Material properties

Table 6 shows the basic properties of all the fractions and Figure 1 and Figure 2 show their particle size distribution . It should be noted that the oven-dried density of ALM-I and FRCA-I (which are the powder contents from Limestone 0/20 and RCA 0/4, respectively) is back-calculated from the experimentally determined specific density and the density of water (1000 kg/m³) based on Eq. (1). In Table 6, the voids ratio is estimated from Eqs. (1) and (2) respectively for aggregate and powder and the fraction mean size is the average of the calculated log mean sizes from the mass-based particle size distributions using the Eqs. (3) and (4). For limestone 0/20, RCA 0/4 and RCA 0/20, the components were also characterized, in addition to the characterization of the complete fractions by following the standard procedure mentioned in Section 2.1.

Table 6. Physical properties of solid fractions.

Fractions	Code	ρ_a [kg/m ³]	ρ_{rd} [kg/m ³]	WA [%]	SC [%]	ρ_{LB} [kg/m ³]	Mean size [mm]	U [-]
Sand 0/1 A	FS1	2671.0	2644.1	0.382	-	1499.2	0.366	0.764
Sand 0/1 B	FS2	2664.5	2651.5	0.184	-	1516.0	0.375	0.749
Sand 0/4	FS3	2694.3	2671.6	0.315	-	1615.6	0.599	0.653

Limestone 2/8	CLM1	2763.6	2727.4	0.481	-	1391.2	3.792	0.961
Limestone 8/20 A	CLM2	2694.8	2665.8	0.404	-	1371.2	14.997	0.944
Limestone 8/20 B	CLM3	2721.8	2677.4	0.610	-	1402.0	13.076	0.910
Limestone 8/20 C	CLM4	2716.5	2682.3	0.469	-	1350.8	10.913	0.986
Limestone 0/20	ALM	2745.0	2717.5	0.368	-	1672.2	2.309	0.625
	ALM-I	-	2658.0	-	26.0	-	0.010	0.717
	ALM-II-1	2759.0	2735.2	0.315	-	1570.0	1.358	0.742
	ALM-II-2	2759.0	2735.2	0.315	-	1574.9	1.237	0.737
	ALM-III	2713.6	2679.3	0.472	-	1356.6	13.181	0.975
RCA 0/4	FRCA	2716.8	2355.6	5.644	-	1281.0	0.722	0.839
	FRCA-I	-	2523.3	-	50.2	-	0.023	1.302
	FRCA-II	2716.8	2355.6	5.644	-	1272.7	0.783	0.851
RCA 0/8 A	ARCA1	2672.8	2168.3	8.707	-	1226.5	1.629	0.768
RCA 0/8 B	ARCA2	2679.5	2215.6	7.815	-	1250.4	1.360	0.772
	ARCA2-I	2733.9	2381.6	5.410	-	1023.8	0.555	1.326
	ARCA2-II	2671.8	2310.9	5.847	-	1087.0	4.077	1.126
RCA 0/8 C	ARCA3	2696.8	2308.8	6.232	-	1356.3	1.441	0.702
RCA 8/20 A	CRCA1	2633.3	2334.3	4.872	-	1249.1	11.322	0.869
RCA 8/20 B	CRCA2	2633.4	2366.2	4.289	-	1170.2	16.029	1.022
RCA 8/20 C	CRCA3	2693.6	2413.6	4.307	-	1237.5	13.353	0.950
RCA 8/20 D	CRCA4	2697.2	2455.4	3.651	-	1270.4	10.726	0.933
RCA 0/20	ARCA4	2652.7	2366.4	4.565	-	1456.6	3.218	0.625
	ARCA4-I	2686.0	2381.6	4.759	-	1248.8	1.046	0.907
	ARCA4-II	2627.7	2355.8	4.400	-	1184.1	14.261	0.990

Remarks: ρ_a is apparent density, ρ_{rd} is oven-dried density, WA is water absorption at 24 h of aggregate, SC is water demand of powder at Vicat

Standard Consistence, ρ_{LB} is loose bulk density, *Mean size* is fraction log mean size, U is voids ratio.

(a) Fine aggregates: 0-1 mm (FS1, FS2), 0-4 mm (FS3, FRCA)

(b) Coarse aggregates: 2-8 mm (CLM1), 8-20 mm (CLM2, CLM3, CLM4, CRCA1, CRCA2, CRCA3, CRCA4)

(c) All-in aggregates: 0-8 mm (ARCA1, ARCA2, ARCA3), 0-20 mm (ALM, ARCA4)

1

Figure 1. Particle size distribution of aggregate.

2

3

Figure 2. Particle size distribution of ALM-I and FRCA-I.

1 It can be seen from Table 6 that the oven-dried densities of the components of a material are comparable to each other.
2 The difference of the volumetric particle size distribution of fractions and the mass-based particle size distribution
3 will be therefore negligible.

4 The apparent density of the RCAs from this study is comparable to that of NAs, which is around 2700 kg/m^3 for all
5 the aggregates (Table 6). However, the oven-dried density of RCAs is significantly smaller than that of NAs and the
6 water absorption ability at 24 h of the RCAs is remarkable higher than that of NAs, which has been noticed as well
7 from other studies [7,10,28,30,49,50]. The oven-dried density is around 2650 kg/m^3 for the NAs and $2200\text{-}2400 \text{ kg/m}^3$
8 for the RCAs used in this study. The voids ratios of coarse limestones and coarse RCAs in this study are quite high
9 (around 0.86-1.0) as compared to the voids ratio of smooth aggregate (e.g., gravel) as noticed from available studies
10 [32,40], given the aggregates have similar size class. Voids ratio of a fraction is amongst others associated with the
11 grading of the fraction. Fractions with enough smaller particles to fill the voids of the coarser particles yield to have
12 lower voids ratio values as noticed for the all-in fractions in Table 6.

13 The water absorption ability at 24 h of NAs in Table 6 is smaller than 0.7%. The water absorption ability at 24h for
14 RCAs used in this study is in between 4% and 9% and lies in the range specified by Marinković et al. [13]. The large
15 variation of the water absorption ability could be attributed to the different sources or batches of the RCAs.

16 Considerable powder content ($< 0.063\text{mm}$) can be seen within FRCA (Figure 1a) and all the all-in aggregates (Figure
17 1c). On the contrary, the powder content within fine NAs is very limited (Figure 1a) and can be neglected. None of
18 the fractions used in this study shows a gap in grading (Figure 1 and Figure 2). It should also be noticed that the water
19 demand at Vicat Standard Consistence of the powder content in RCA 0/4 (FRCA-I) is almost twice the value obtained
20 for the powder content in Limestone 0/20 (ALM-I) (which are 50.2% and 26%, respectively).

21 The properties of aggregates in Table 6 are characterized by following the standard procedures. This means that the
22 properties of the powder content from the fine aggregates and all-in aggregates were not incorporated in the
23 determination of the apparent density, oven-dried density and water absorption at 24h due to the wet sieving (as
24 mentioned in Section 2.1). However, this powder content was considered in determining the loose-bulk density and
25 particle size distribution of the materials. Dewar [41] recommended that the fines of sands (powder content) should
26 be tested for voids ratio in water rather than in the air. Taking into consideration the powder content ALM-I and
27 FRCA-I (from ALM and FRCA, respectively), the properties of ALM, ALM-II-2 and FRCA were re-calculated (as
28 shown in Table 7) by using the weight shares and properties of all the split components from Table 2 and Table 6,

respectively.

It can be seen that despite the fact that the powder content is considerable within ALM (2.5%) and FRCA (2.9%), it has limited effect on the properties of the original fractions (fraction mean size and voids ratio for ALM are respectively 2.214 mm and 0.626 after re-calculation in comparison to 2.309 mm and 0.625 before the re-calculation; for FRCA these values are 0.708 mm and 0.843 after the re-calculation in comparison to 0.722 mm and 0.839 before the re-calculation). It can be expected as well that the powder content of the aggregates in this study would have limited effect on the packing density of aggregate mixtures with these aggregates. Therefore, the fraction properties listed in Table 6 are used for the validating program in this study.

Table 7. Estimated physical properties of ALM and FRCA1 based on the characteristics and weight share of all individual components.

Fractions	Code	ρ_a [kg/m ³]	ρ_{rd} [kg/m ³]	WA [%]	ρ_{LB} [kg/m ³]	Mean size [mm]	U [-]
Limestone 0/20	ALM	2745.0	2718.6	0.382	1672.2	2.214	0.626
	ALM-II-2	2759.0	2732.6	0.315	1574.9	1.175	0.735
RCA 0/4	FRCA	2716.8	2360.4	5.644	1281.0	0.708	0.843

Remarks: ρ_a is apparent density, ρ_{rd} is oven-dried density, WA is water absorption at 24 h of aggregate, ρ_{LB} is loose bulk density, *Mean size* is fraction log mean size, U is voids ratio.

3.2. Voids ratios of aggregates mixture

The voids ratios of aggregate mixtures were predicted based on Dewar's model, straightforward in case of no size class interference of the fractions. However, in case of size class interference, as mentioned in Section 1 the wide-graded fraction(s) should be split into its components and the finer to coarser fractions should be strictly combined step-by-step (except for materials which have close size, these can be pre-combined). Based on this, three cases of voids ratio predicting of aggregate mixtures with graded fraction(s) can be identified in this study:

- (1) Fractions without size class interference;
- (2) Size class interference: finer with wide-coarser fraction;
- (3) Size class interference: coarser with wide-finer fraction.

The voids ratios from both theoretical prediction and experimental determination are shown in Figure 3. NN*0.2 is an

1 additional interaction group which includes all-in NA Limestone 0/20 and coarse Limestone 8/20 (Figure 4).

2

(m) NN0.75, $r=0.835$

(n) NR0.75, $r=0.755$

(o) RR0.75, $r=0.706$

* Mixture with fractions having size class interference.

Figure 3. Voids ratios from mixing aggregates at different replacing levels (Dewar: predictions based on Dewar theory; Lab: determined experimental value).

Figure 4. Voids ratios from mixing aggregates at different replacing levels for NN*0.2 ($r = 0.177$) (Dewar: predictions; Lab: determined experimental value).

3.2.1. Fractions without size class interference

The aggregate mixtures with fractions which do not have size class interference are NN0.03, NR0.03, RR0.03, NN0.1, NR0.1, RR0.1, NN0.2, NN0.4, NR0.4, NN0.75, NR0.75, RR0.75, NN1.0, NR1.0 and RR1.0. The binary packing of these mixture groups were predicted by the Direct Predicting Method (DPM, predictions made based on the properties of the materials from Table 6), in comparison with the experimental values as shown in Figures 3a-g, j-k and m-r. In general, the predictions of voids ratio based on Dewar's packing model of combined fractions without class interference are very close to the experimental ones. Significant deviations of the experimental voids ratios to the predictions have been seen for the group RR0.03, NR0.1 and RR0.1, where RCAs (FRCA and ARCA 3) are present

(Figures 3c and e-f) and aggregate mixtures are with small size ratio values. A discussion follows in Section 3.3.

3.2.2. Size class interference: finer with wide-coarser fraction

Dewar [41] stated clearly that when finer fraction is to be blended with wide-coarser fraction (which are the cases NR*0.2 and RR*0.4 in this study), the coarser fraction should be split. Therefore, the predictions of voids ratios for NR*0.2 and RR*0.4 were made based on the two-steps predicting method (TSPM, by following the principles specified in Section 1) where the equivalent amount of the finer component (calculated by the share of this part to the complete fraction based on Table 2) of the wide-coarser fraction was combined with the finer fraction in the mixture first and the mixed finer fractions were further blended with the equivalent coarser component from the wide-coarser fraction theoretically. The predicting curves shown in Figure 3h and l are the ones following the TSPM for the aggregate mixtures NR*0.2 and RR*0.4, respectively.

Predictions of the voids ratios of the interaction groups NR*0.2 and RR*0.4 made from the TSPM have good matches with the experimental ones (Figure 3h and l). Furthermore, the influence of predicting methods (DPM and TSPM) on the voids ratio predicting accuracy will be addressed in Section 3.2.4.

3.2.3. Size class interference: coarser with wide-finer fraction

Although Dewar [41] did not explicitly mention the procedure for aggregate mixtures which incorporate coarser with wide-finer fraction, the voids ratio predictions of these aggregate mixtures (NN*0.2 and RR*0.2 in this study) can also be made by the TSPM: theoretically mix the equivalent coarser component from wide-finer fraction (calculated by the share of this part to the complete fraction based on Table 2) with the coarser fraction and then combine the mixes with the equivalent amount of finer component from the wide-finer fraction. The prediction curves of these aggregate mixtures by following the TSPM are shown in Figure 3i and Figure 4, in comparison with the experimental values. Significant deviations of the experimental voids ratios to the predictions occur for NN*0.2 and RR*0.2, especially in the high fine fraction value zones.

For these two special cases, the prediction was made from simulating the equivalent aggregate mixes of the 8/20 from 0/20 with 8/20 from the other material first (Figure 5b and 6b) and then mixing the 0/8 from 0/20 with the simulated mixes 8/20. Examples are shown by Figure 5c and 6c and here explained. The fractions with size 8/20 have quite similar voids ratio and mean size values. As a result, the voids ratio diagram of aggregate mixes with these fractions tend to be linear (Figure 5b and 6b). When the finer fraction 0/8 from the all-in fraction 0/20 is to be blended with the 8/20 aggregate mixes (here intended to be done for all triangular points in Figure 5b and 6b), several voids ratio

diagrams (similar to Figure 5c and 6c) are formulated of which only one point in each of these modelled curves is relevant. To be more specific, relevant points in different diagrams (similar to Figure 5c and 6c) are situated at fine fraction values from 0 (when 0/20 is not present) up to the volume share of 0/8 to 0/20 (which are 0.570 and 0.738 for ARCA4 and ALM, respectively). The voids ratio predicting curves of 0/20 with 8/20 (Figure 5a and Figure 6 a) are then a combination of these relevant points. When size ratio is incorrect, it will have great influence on the medium fine fraction zone of the predicting curves of fractions 0/8 and 8/20 [48] (e.g., Figures 5c and 6c), accordingly it will be reflected as the higher fine fraction value zone in the predicting curves of fractions 0/20 with 8/20 (Figures 5a and 6a).

Figure 5. Predicting steps for RR*0.2 by TSPM (RP0.6: the aggregate mixtures by replacing 60% of CRCA3 with ARCA4 by volume; Dewar: predictions based on Dewar theory; Lab: determined experimental value; Modelling: prediction by Dewar's model with equivalent amount of the materials from the original combinations; RCAMix: one specific RCA mix, here as an example the one indicated in Figure 5b by RP 0.6).

Figure 6. Predicting steps for NN*0.2 by TSPM (RP0.9: the aggregate mixtures by replacing 90% of CLM3 with ALM by volume; Dewar: predictions based on Dewar theory; Lab: determined experimental value; Modelling: prediction by Dewar's model with equivalent amount of the materials from the original combinations; LMMix: one specific limestone mix, here as an example the one indicated in Figure 6b by RP 0.9).

3.2.4. Direct Predicting vs. two-steps predicting

TSPM was applied for the mixture groups that have the size interference issue, which are NR*0.2, RR*0.4, NN*0.2 and RR*0.2. Figure 7 shows the predictions from both DPM and TSPM for these interaction groups.

Figure 7. Theoretical voids ratio for mixtures with size class interference issues from DPM and TSPM based on Dewar model in comparison to the experimental values (Lab).

The TSPM in comparison to the DPM has decreased the discrepancies between experimental voids ratios from the predictions for the test groups NR*0.2 and RR*0.4, as shown by Figures 7a-b, respectively. For the test groups NN*0.2 and RR*0.2, the predicting curves by TSPM are quite similar to those from DPM and significant differences between experimental results and predictions made from both DPM and TSPM can be noticed from Figures 7c-d graphically. The reason was discussed in Section 3.2.3 and relates to the influence of the size ratio.

3.3. Differences of voids ratios

Without applying the size ratio adjustment factor, there can be unacceptable discrepancies between the experimental voids ratios and the predictions from Dewar's Model (either from TSPM or DPM) as shown in Figures 3-4 and Figure 7. An adjustment factor F for correcting the size ratio of the aggregate mixtures for different fitting scenarios can be necessary.

The corresponding differences (both $Diff$ and $\overline{Diff}$ calculated from Eqs. (11) and (12)) of the experimental voids ratios to the predicting ones after applying the adjustment factors are displayed in Figure 8 and Figure 9 for the interaction test program in this study. For the groups whose fractions have size class interference (NN*0.2, NR*0.2, RR*0.2, RR*0.4), the adjustment factor can only be applied to the predictions made from DPM and not for TSPM. However, the differences of the voids ratios without fitting scenarios are calculated based on the predictions made from both DPM and TSPM as shown in the Figure 8 and Figure 9.

Figure 8. Calculated differences $Diff$ of different fitting scenarios for the interaction tests in this study.

Figure 9. Calculated average differences $\overline{Diff}$ of different fitting scenarios for the interaction tests in this study.

The differences from different fitting scenarios were calculated as well for the interaction tests that were carried out by Dewar [41] and the results are shown in Figure 10 and Figure 11. It should be noticed that the dataset from Dewar [41] excludes fractions which have size class interference and only DPM is applied for calculating the differences.

Figure 10. Differences $Diff$ of different fitting scenarios for the interaction tests carried out by Dewar (calculations based on [41]) (size ratios of all groups except JDD1 AB and JDD1 bc are smaller than 0.5).

Figure 11. Average differences $\overline{Diff}$ of different fitting scenarios for the interaction tests carried out by Dewar (calculations based on [41]) (size ratios of all groups except JDD1 AB and JDD1 bc are smaller than 0.5).

In general, the adjustment factor could increase the predicting accuracy of the voids ratio for aggregates mixtures since the differences of the voids ratios can be decreased considerably after the calibration, as shown in Figures 8-11. However, the single point fitting SPF0.2, SPF0.3, SPF0.6, SPF0.7 and SPF0.8 may also increase the differences of the experimental voids ratio to the adjusted predicting voids ratio based on Dewar's model. On the contrary, GF, SPF0.4, TPF0.3-0.5 and TPF0.4-0.6 show good performance in limiting the differences, irrespective of the sources of the data (this study or study from Dewar). The fitting scenario SPF0.5 shows good performance in lowering the differences from the test results from this study (Figures 8-9) but it could increase the differences for the dataset from Dewar (Figures 10-11). After calibrating the size ratio with the adjustment factors from the fitting scenarios GF, SPF0.4, TPF0.3-0.5 and TPF0.4-0.6, the calculated average differences $\overline{Diff}$ of the experimental voids ratios to the predictions can be limited within 0.003 for the interactions from this study as well as from Dewar [41].

It seems that the single point fitting scenario SPF0.4 can efficiently calibrate the size ratio of aggregates mixtures, in comparison to the GF, TPF0.3-0.5 and TPF0.4-0.6. The adjustment factors from the fitting scenario SPF0.4 of the interaction groups in this study are summarized in Table 8.

Table 8. Adjustment factors F from the fitting scenario SPF0.4 for the interaction groups in this study.

	NA&NA	NA&RCA	RCA&RCA
	NN0.03: 1.569	NR0.03: 1.344	RR0.03: 2.950
	NN0.1: 1.00	NR0.1: 2.630	RR0.1: 3.103
	NN0.2: 1.340		
F values	NN*0.2: 2.280	NR*0.2: 1.725	RR*0.2: 1.588
	NN0.4:1.474	NR0.4: 1.119	RR*0.4: 1.957
	NN0.75: 1.135	NR0.75: 1.475	RR0.75: 1.126
	NN1.0: 0.770	NR1.0: 8.750	RR1.0: 6.377

After the calibrations, the predictions based on Dewar have good matches with the experimental voids ratios of aggregate mixtures, which could be demonstrated with the interaction groups RR0.03, NR0.1, RR0.1, NN*0.2 and RR*0.2 with the fitting scenario SPF0.4 (Figure 12). For the other interaction groups in this study, adjustment of size ratio might not be necessary. High adjustment factors (which are 8.750 and 6.377) were found from SPF0.4 for NR1.0 and RR1.0 and it has limited effect in decreasing the differences of voids ratios from experimental ones to the predictions, which confirmed the finding from Liu et al., [48] that the voids ratio predictions are less sensitive in the region of low fine fraction values when size ratio is higher. The discrepancies of voids ratios of NR1.0 and RR1.0 should be attributed to the wrong estimation of voids ratios from finer and coarser material within the interaction tests.

Practically, it is recommended to estimate the size ratio adjustment factor F from adjusting the predicted voids ratio to the experimental one for an aggregate mixture with 40% finer aggregate and 60% coarser aggregate (SPF0.4), when calibration of the Dewar's model is needed. Calibration requires in this way a limited effort and enhances the accuracy of the predictions considerably.

(a) RR0.03, $F \times r=0.131$

(b) NR0.1, $F \times r=0.290$

(c) RR0.1, $F \times r=0.395$

(d) NN*0.2, $F \times r=0.403$

(e) RR*0.2, $F \times r=0.383$

Figure 12. Examples showing the voids ratios from experiments and predictions before and after calibrating the size ratios from SFP0.4 (Dewar: predictions based on Dewar theory without size ratio adjustment factor; Fitting: predictions based on Dewar theory after applying size ratio adjustment factor; Lab: determined experimental values).

The particle shape, texture, surface and density are partially considered in Dewar's packing model from the evaluation of the voids ratio of the aggregate. Note that the predicted voids ratios of the natural aggregate mixes (NN*0.2) with natural all-in aggregate (Limestone 0/20) also do not correspond with the experimental values and an adjustment factor F is recommended to be applied on the predicted voids ratios. Similar reasons as identified for the RCAs can here be drawn. The evaluation of the log mean size could be very sensitive to the particle size distribution characterized from the sieving process due to the irregularities of the particles.

3.3.1. Influence of the size ratio

Figure 9 and Figure 11 show big average differences $\overline{Diff}$ of experimental voids ratios to the predictions in the low size ratio groups (0~0.5 in this study, all the series except JDD1 AB and JDD1 bc from Dewar [41]). In high size ratio zones (0.5~1 in this study, 0.599 of JDD1 AB and 0.505 of JDD1 bc from Dewar [41]), the average voids ratios differences $\overline{Diff}$ from the experimental tests to the predictions are quite small (smaller than 0.003 in both Figure 9 and Figure 11).

3.3.2. Influence of the interaction types

Regardless of the interaction types (NA&NA, NA&RCA and RCA&RCA), the voids ratio predictions based on Dewar's model have in general good matches with the experimental ones (Figure 3). The adjustment factors F from SPF0.4 (Table 8) calculated for the NA&NA groups (except NN*0.2) are quite comparable to the values which were adopted by Dewar (0.6-1.6) [41]. For the interaction groups NA&RCA and RCA&RCA, higher adjustment factors may be adopted as shown in Table 8. The reasons to explain the higher adopted adjustment factors could be the

irregular particle shape (especially for the RCA) and the continuously graded features of the fractions from crushing process (especially for the graded all-in fraction, e.g., ALM and ARCA4).

Pradhan et al., [1] noticed in their study that the theoretical packing density predicted from the CPM does not reflect good correlation with their experimental results for both NAs and RCAs when the compaction factor K was taken as 4.5 for dry rodding procedure to prepare dry aggregate packing and the adoption of a higher compaction factor K allowed to improve the predicting accuracy. It has also been noticed by Dewar [41] that particles with high surface friction or angular shape might need higher compaction energy in order to achieve equivalent compaction state. As a result, a higher compaction factor is required when Pradhan et al., [1] calibrated the packing density from CPM to the real one. Comparing to that, the packing theory of Dewar [41] is based on the loose bulk density of aggregates or aggregate mixtures where no compaction energy is introduced in the packing. The surface friction or the angularity of the particles are partially considered within the estimated voids ratio of the aggregate fractions. The deviations of experimental voids ratios to the predictions should be attributed mainly to the inaccurate fraction mean size values and further to the size ratios of the aggregate mixtures.

3.3.3. Single-sized fraction vs. graded fraction

The fractions present in the interaction series JDD1, JDD2 and JDD3 Ac from Dewar [41] are single-sized fractions in comparison to the graded fractions presented in other interaction series from Dewar [41] and from this study. Series JDD3 (except JDD3 Ac) from the study of Dewar [41] are mixtures which incorporate multi-sized fraction (a combination of single-sized fraction material). JDD4 from Dewar [41] and interaction groups from this study include graded fractions.

Apparently, the voids ratios differences $Diff$ and average differences $\overline{Diff}$ for the interaction groups with single-sized fractions from the study of Dewar [41] (Figures 10 and 11) are very small, which are up to 0.012 and 0.002, respectively. The voids ratios differences $Diff$ and average differences $\overline{Diff}$ of the other groups (groups with graded fraction) are in general higher than the groups with single-sized fractions (Figures 8-11). Despite that graded materials are used, the voids ratios differences $Diff$ and average differences $\overline{Diff}$ of group NN0.03, NR0.03, NN0.1, NN0.2, NR*0.2, NR*0.4, NN0.75, NR0.75, RR0.75, NN1.0, NR1.0, RR0.1, series JDD3 (except JDD3 Ac), JADD4 G2 and JDD4 G4 (up to 0.023 for $Diff$ and 0.003 for $\overline{Diff}$, respectively) are quite comparable to those of the groups with single-sized fractions from Dewar [41] (up to 0.012 for $Diff$ shown in Figure 10 and 0.002 for $\overline{Diff}$ shown in Figure 11, respectively).

4. Conclusions

This paper presents the binary packing of NA&NA, NA&RCA and RCA&RCA both theoretically and experimentally. The PPM theory from Dewar was used for the prediction based on the physical properties of the materials. Following conclusions can be drawn with respect to the content of this study:

- 1) Despite that considerable powder content has been found within all-in fractions and one fine RCA fraction, this certain amount of powder has rather limited influence on the packing density of the fraction itself and it is expected that it has limited influence on the packing density of the aggregate mixtures made with it. However, the fine particles in the RCA and NA (particles smaller than 0.125 mm or 0.250 mm) could have important influence on the voids ratio in the concrete mix design. It could be possible that these particles in the PPM should be allocated to the powder fraction instead of the aggregate fraction. Future study should focus on evaluating the effect that the powder content has on the packing density of concrete mixtures, as well as on fresh and hardened concrete properties.
- 2) The size ratio of aggregate mixtures plays a pivotal role in determining the mixtures voids ratio from the Dewar's model. Regardless of the aggregate types, an adjustment factor for calibrating the size ratio could be required. The reasons behind this could mainly be attributed to aggregate particle shape and its graded particle size distribution. The compaction energy could be important in predicting aggregate mixtures packing density when other packing models (e.g., CPM) are applied, but it is not considered in Dewar's packing model. The adjustment factor for implementing RCA in aggregate mixtures could be higher than for implementing pure NAs.
- 3) The fitting scenarios GF, SPF0.4, TPF0.3-0.5 and TPF0.4-0.6 from adjusting the size ratio can improve the voids ratio predicting accuracy of Dewar's model and practically it is advised to estimate the adjustment factor from the scenario SPF0.4 (where the replacing level by finer material is 0.4). However, when the value of size ratio is high (0.5-1), adjustment of size ratio might not be necessary.
- 4) In case of size class interference, it is advised to split the graded fraction into its components, to characterise the components separately and use the TSPM based Dewar model. This typically occurs in case of all-in fractions.
- 5) The adoption of TSPM in comparison to DPM can increase the predicting accuracy of the voids ratios for

aggregate mixtures with fractions that have overlapping size classes, but in some cases it might not be sufficient to increase the predicting accuracy. Application of an adjustment factor on the size ratio from the DPM could tackle the discrepancies. Further studies are required to evaluate its influence on the prediction of concrete mixtures packing density or its influence on proportioning concrete mixes.

The overall study concludes that the Dewar Model can be used to predict packing density of aggregate mixtures, regardless of the presence of RCAs. The estimation of the representative parameters of RCA used in the PPM can be more sensitive in comparison to those of NA but this could be tackled with the use of an adjustment factor for the size ratio. More emphasis in the future should be laid on predicting the packing density of concrete mixtures and on proportioning eco-efficient concrete mixes based on Dewar's model.

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