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RESEARCH ARTICLE OPEN ACCESS

Influence of Intermediate-Sized Particle Content on Traditional Dry-Rodded and Vibrated Aggregate Packing

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ABSTRACT
The addition of standard intermediate aggregate (IA) content may provide desired intermediate-sized aggregate particle (ISA) content that can enhance the aggregate gradation and predictability of the aggregate packing (k) and Portland cement concrete consistency. This study evaluates the effect of the ISA on the average variation between traditional dry-rodded and vibrated aggregate packing (Δk) results. Gradation factors were determined and plotted on the Modified Coarseness Factor Chart (MCFC) seeking to identify Δk-ISA content correlations and to investigate a relationship between ISA and concrete consistency. The aftermath of 96 tests were grouped in three intervals determined by gradation curve resemblance. The results indicated that when ISA was between 25 and 27 % (by weight), Δk reached its lowest level: 1.7 %. Also, the optimized gradation (B6) displayed ISA = 26 % and fell right at the center of the MCFC's Workability Box (WB). Lastly, aggregate blends with 10 < IA < 11 % (by weight) translated into 25 < ISA < 27 % and surrounded the WB of the MCFC. The study concludes that adding IA to concrete can increase adherence between concrete design and placement, besides providing better consistency to concrete.
Keywords – Aggregate optimization, Concrete, Gradation, Intermediate-sized aggregate, Packing, Portland cement, MCFC, Slump.

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I. INTRODUCTION

Aggregate proportions, Maximum Aggregate Size (MS), Nominal Maximum Size of the aggregate (NMS), Particle Size Distribution (PSD), and aggregate packing (k) typically dominate mechanical and physical properties of Portland cement concrete [1,2]. Thus, designing concrete based on optimized gradations and packing may result in 25 % less cement content to reach a targeted compressive strength and less water-reducing admixture to obtain a required consistency.

Given the importance of the effects of aggregates on concrete performance, this study evaluated the influence of Intermediate-Sized Aggregate particle content (ISA) on the traditional dry-rodded (kr) and vibrated (kv) aggregate packing. The methodological approach consists of relating aggregate content retained within the sieves 2.36 and 9.5 mm (ISA) to variations (Δk) between dry-rodded and vibrated aggregate packing, as well as to the estimated concrete consistency using the Modified Coarseness Factor Chart (MCFC).

This study argues that blending an appropriate amount of intermediate aggregate to traditional fine-coarse binary blends can reduce the variability in the aggregate blend compaction when subjected to kr and kv methods. Also, well-suited ISA contents can lead to better estimates of concrete consistency due to the potential similarity of aggregate arrangements under both rodded and vibrated compaction energies applied.

II. BACKGROUND

2.1 Aggregate Grading

Aggregate gradation charts are typically used to plot the cumulative percentages aggregate particles passing through a series of standard sieve sizes. The gradation of the aggregate blend in concrete has a significant impact on concrete workability and material costs.

Binary blends of most concrete mixtures are composed of: fine aggregate, with particles smaller than 4.75 mm; and coarse aggregate, with particles larger than 4.75 mm. A well-graded distribution, covering all particle sizes, frequently contains a higher percentage of ISA and overall smaller portions at the extremes. Such gradation is often described as a haystack when plotted on the percent retained charts [3].

It is also crucial to define the MS as the smallest sieve size that retains 15 % or more of the particles, and the Fineness Modulus (FM) of fine aggregates as the cumulative percentage of particles retained within the standard sieves 150 μm and 37.5 mm [3], which are key properties of aggregates and have high impact on concrete performance.

2.2 Aggregate Optimization

Concrete practitioners have already specified and endorsed traditional optimized aggregate gradations to enhance concrete properties. However, very few comprehensive optimization procedures are readily available at the disposal of engineers [4].

Theoretical and empirical approaches can be used to obtain a typically optimized aggregate gradation, and their primary premise is similar: blending two aggregates usually provides a gap-graded gradation due to the absence of ISA, having a peak-valley-peak distribution. It is known that achieving a traditional optimized gradation often requires the combination of at least three differently sized aggregates [4,5].

Commonly used techniques to develop traditional optimized aggregate gradations are the MCFC; the percent retained chart; and the Power Curve. All of them aim to determine a target gradation, and then to select an optimized blend among the available options [4].

To clarify the MCFC applications, first it is necessary to introduce the Coarseness Factor (CF), the adjusted Workability Factor (WF_{adj}), and the parameters Q, ISA, and W, as shown in equation (1) and equation (2).

$$CF = [Q / (Q + ISA)] \times 100\% \quad (1)$$

Where:
CF = coarseness factor,
Q = cumulative % retained on the sieve 9.5 mm,
ISA = % retained within sieves 2.36 mm and 9.5 mm.

$$WF_{adj} = W + [2.5\ \% \times \Delta C / WT] \quad (2)$$

Where:
WF_{adj} = adjusted workability factor,
W = cumulative % passing the 2.36 mm sieve,
ΔC = cement content difference to 335 kg/m^3,
WT = weight of cement bag as 42.6 kg.

2.3 Aggregate Packing

Aggregate packing (k) relates to the volume of cement paste needed to fill the gaps in between the aggregates, as well as the volume of cement paste to separate particles and provide mobility to concrete. Typically, kr is used in most current mixture designs, and concrete mixtures are subject to vibration in the United States.

Moreover, k is the ratio between solids volume (P_v) and compacted bulk volume (V). Packing is dependent on three parameters: the shape of the grains; the size of the grains; and the energy and packing technique. Aggregate packing of round aggregate blends appears to be about 12 % greater than outcomes obtained from crushed aggregate blends [6]. Since most theoretical models consider monosized or random spherical particle shapes to determine k, these theoretical simulations may generate fewer voids to fill with cement paste than the experimental k [7]. These models containing spherical blends may often lead to optimistic results in which less cement paste is required to fill the gaps between grains. Hence, most simulations may unrealistically predict the use of lower cement paste content than actual concrete mixtures require.

However, some models are calibrated using aggregate dimensions and k to reduce result variations to established theoretical models (e.g., Toufar's). This procedure can significantly reduce experimental efforts [8].

Some parameters are required to determine k accurately. For instance, P_v is the actual aggregate particles volume [7] as shown in equation (3).

$$P_v = W / \rho \quad (3)$$

Where:
P_v = solids volume, m^3,
W = mass of the aggregates, kg,
ρ = density of the aggregates, kg/m^3.

The compacted bulk volume V is the volume occupied by packed aggregate particles, as expressed in equation (4).

$$V = W / M \quad (4)$$

Where:
V = compacted bulk volume, m^3,
W = mass of the aggregates, kg,
M = compacted dry-rodded unit weight of the aggregates, kg/m^3.

Thus, k is the ratio between P_v and V [7] as seen in equation (5).

$$k = P_v / V \quad (5)$$

Where:
k = aggregate packing,
P_v = solids volume, m^3,
V = compacted bulk volume, m^3.

2.4 Power Curve

The maximum density of aggregate gradations has been known for about 100 years [9]. Fuller and Thompson initially proposed the Power curve index (n) as 0.50 [10], and it was later adjusted to 0.45 [11]. Since then, each standard sieve opening is raised to the 0.45 power. The Power curve is a straight line representing the maximum aggregate blend density, connecting the origin to the aggregates' NMS. The best-fit gradation to the Power curve can provide aggregate proportions, although concrete mixtures using very dense gradations are usually harsh [9,11,12]. The Power curve equation is shown in equation (6).

$$P_d = 100 \times (d / D_{max})^n \quad (6)$$

Where:

P_d = particles passing a sieve opening, %,
d = sieve opening, mm,
D_{max} = maximum sieve opening, mm,
n = 0.45.

2.5 Aggregate Proportioning in Concrete

The Dry-Rodded Unit Weight (DRUW) of the coarse aggregate is a valuable property because it provides the maximum possible volume of rodded aggregate per unit volume of concrete. The higher the DRUW of coarse aggregate used, the more economic benefit can be obtained in concrete due to the reduction of voids that need to be filled with cement paste. Also, for a given FM of the fine aggregate, the larger the MS, the higher the coarse aggregate volume used in concrete [3]. The addition of IA can be beneficial to concrete due to the better filling of additional voids in aggregate, and the reduction in friction between fine and coarse aggregate. As a result, concrete durability, mobility, and compressive strength can be enhanced, while a higher economic worth can be provided to the final material [13].

2.6 Concrete Consolidation

The typical goal of concrete preparation is its placement as near as possible to the final location. Producers usually place batched aggregates, cement, water and eventually chemical admixtures and other cementitious materials in mixers according to the mixture design. During mixing, air bubbles are formed within the cement-paste-mortar, then the concrete is transported to the job site [3]. Whether internal or external, most concrete mixtures need vibration during placement to move air bubbles up and out of the concrete, and to provide ingredients homogeneity. After the vibration process ends, all ingredients in concrete are supposed to occupy their final positions [3].

III. MATERIALS AND METHODS

3.1 Aggregates

The fine aggregate (FA) used in this study was silica sand from the supplier GA397 according to the FDOT (Florida Department of Transportation) producers list. The intermediate coarse aggregate (IA) used was the Miami Oolite Limestone #89 from the mine 87,090 (supplier code TM447). The coarse aggregate (CA) was the Miami Oolite Limestone #57 from the same IA quarry. Table 1, 2, and 3 show fine, intermediate, and coarse aggregate properties, respectively. Fig. 1 shows the individual gradation curves of the FA, IA, and CA.

Table 1 Physical Properties of Fine Aggregate.

Physical Properties	Standard	Value
Materials < 75 µm	ASTM C117-17 [14]	0.2 %
Fineness Modulus	ASTM C136-14 [15]	2.34
SSD Specific Gravity	ASTM C128-15 [16]	2.70
Apparent Specific Gravity	ASTM C128-15 [16]	2.75
Bulk Specific Gravity	ASTM C128-15 [16]	2.69
Absorption	ASTM C128-15 [16]	0.3 %

Table 2 Physical Properties of Intermediate Aggregate.

Physical Properties	Standard	Value
Materials < 75 µm	ASTM C117-17 [14]	1.7 %
Nominal Maximum Size	ASTM C33-16e1 [17]	9.5 mm
SSD Specific Gravity	ASTM C127-15 [18]	2.45
Apparent Spec. Gravity	ASTM C127-15 [18]	2.61
Bulk Specific Gravity	ASTM C127-15 [18]	2.35
Absorption	ASTM C127-15 [18]	4.2 %

Table 3 Physical Properties of Coarse Aggregate.

Physical Properties	Standard	Value
Materials < 75 µm	ASTM C117-17 [14]	1.5 %
Nominal Maximum Size	ASTM C33-16e1 [17]	19 mm
SSD Specific Gravity	ASTM C127-15 [18]	2.42
Apparent Spec. Gravity	ASTM C127-15 [18]	2.59
Bulk Specific Gravity	ASTM C127-15 [18]	2.32
Absorption	ASTM C127-15 [18]	3.9 %

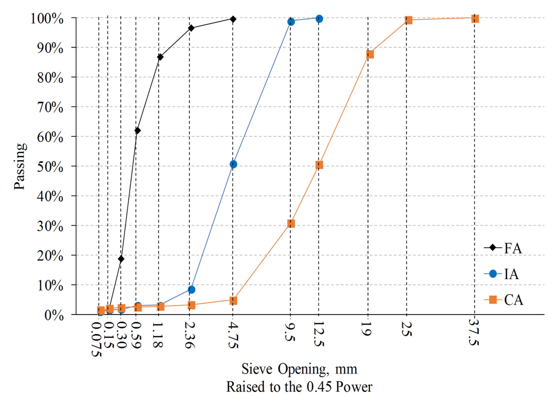

Fig. 1 Particle Size Distribution of Fine, Intermediate, and Coarse Aggregates.

3.2 Aggregate Blends

Proportions of aggregate blends required a broad range of combinations. The ten combinations shown in Table 4 have the percent of IA varying from 2.5 to 18 % by weight. Due to this extensive array, many possible blend combinations were determined as shown in Fig. 2. Similar-shape curves were grouped as shown in Fig. 3, 4, and 5 because size and shape of aggregates are some of the key influencing factors to aggregate compaction so that gradation curves had to present similar overall slopes to provide appropriate comparison; and, because comparable-shape curves are supposed to provide similar ISA content.

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Table 4 displays other aggregate-blend proportions, as well as MCFC factors. Table 5 shows aggregate blend gradations.

Table 4 Aggregate Blend Proportions and MCFC Factors (By Weight).

Blend	CA, %	IA, %	FA, %	Total, %	CF, %	WF, %
B1	48.750	2.500	48.750	100	66	49
B2	47.500	5.000	47.500	100	63	48
B3	47.125	5.750	47.125	100	62	48
B4	46.250	7.500	46.250	100	60	47
B5	55.000	10.000	35.000	100	60	37
B6	56.700	10.300	33.000	100	60	35
B7	58.200	11.200	30.600	100	60	33
B8	42.500	15.000	42.500	100	52	44
B9	41.250	17.500	41.250	100	50	43
B10	41.000	18.000	41.000	100	50	43

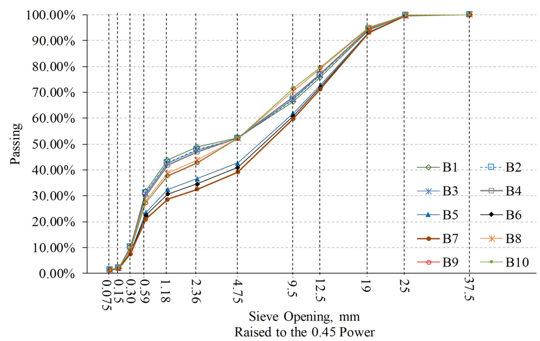

Fig. 2 Particle Size Distribution of Aggregate Blends.

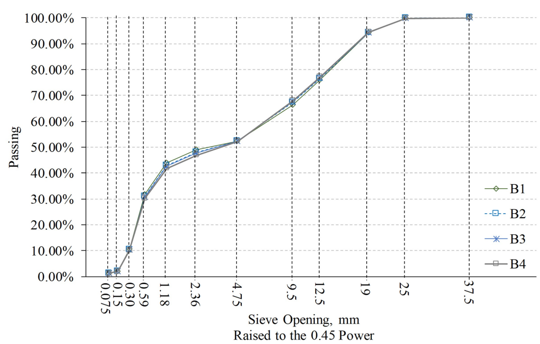

Fig. 3 Particle Size Distribution of Aggregate Blends B1, B2, B3, And B4.

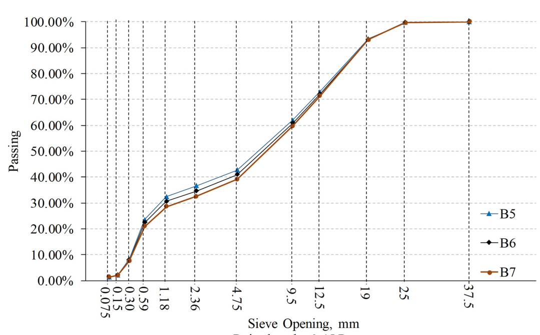

Fig. 4 Particle Size Distribution of Aggregate Blends B5, B6, B7.

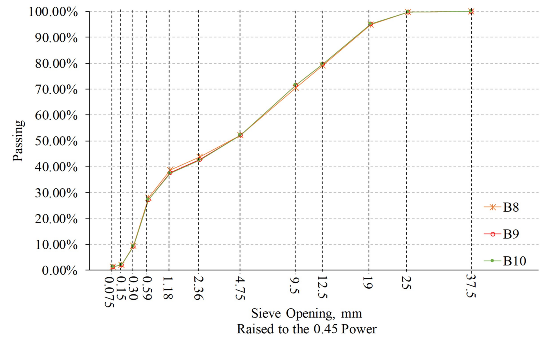

Fig. 5 Particle Size Distribution of Aggregate Blends B8, B9, And B10.

Table 5 Aggregate-Blend Combined Gradations.

Sieve, mm	B1, %	B2, %	B3, %	B4, %	B5, %	B6, %	B7, %	B8, %	B9, %	B10, %
37.5	100	100	100	100	100	100	100	100	100	100
25	100	100	100	100	100	100	100	100	100	100
19	94	94	94	94	93	93	93	95	95	95
12.5	76	77	77	77	73	72	71	79	80	80
9.5	66	67	67	68	62	61	60	71	71	72
4.75	52	52	52	52	43	41	39	52	52	52
2.36	49	48	48	47	37	35	33	44	43	43
1.18	44	43	43	42	32	31	29	39	38	37
0.59	32	31	31	30	24	22	21	28	27	27
0.30	11	10	10	10	8.2	7.9	7.5	9.4	9.2	9.2
0.15	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0
0.075	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.3	1.3	1.3

3.3 Aggregate Packing Testing Procedure

Aggregate packing was systematically determined to achieve accurate results. The k tests were conducted as follows: samples of 12.8 kg for dry-rodded and 8.6 kg for vibrated packing were mixed thoroughly before horizontal layers of aggregates were poured into the measure in three equal layers vibrated for 30 seconds each, and the distance between cylinder rim and the top of the samples were measured at four evenly distributed locations. Fig. 6 shows a traditional dry-rodded packed sample, while Fig. 7 and 8 show a Vebe apparatus and compacted sample measurement, respectively.

Fig. 6 Traditional Dry-Rodded Packing Test.

Fig. 7 Vebe Apparatus for Vibrated Aggregate Packing Test.

Fig. 8 Second Step of The Vibrated Packing Test on Ternary Aggregate Blends, Measuring the Distance Between the Top Vibrated Sample and Rim.

The sample weight for vibrated packing was designed to fit the Vebe measure, which has a volume of 0.0093 m^3. The average loose unit weight of the combined aggregates was tested, resulting in 1,121 kg/m^3. Then, aggregate samples had to weigh no more than 10 kg to favor operational applicability of the tests.

3.4 Aggregate Optimization Procedure

Gradation optimization technique provides a well-suited approach to employ multi-source aggregates to be blended and optimized. Optimizations were performed as follows: aggregate gradations were determined using the standard sieve series; aggregate blends were mathematically combined based on initial trial proportions; the percent passing charts were prepared; desired gradations were determined based Talbot and Richart's [11] Power curve's equation and n = 0.45; CF and WF of combined gradations were calculated and plotted on the MCFC; traditional optimized gradation proportions were calculated aiming the center of the workability box (WB), where WF = 35 % and CF = 60 %.

IV. RESULTS AND DISCUSSION

This investigation aimed to evaluate the influence of intermediate-sized aggregate particle (ISA) content on the traditional dry-rodded (kr) and vibrated (kv) aggregate packing by arguing that selecting the appropriate commercial intermediate aggregate (IA) contents can increase the adherence between mixture design and concrete consistency. The decision on the optimal aggregate blend needed was based on the least numerical difference between the dry-rodded and vibrated packing (Δk).

Each aggregate blend gradation curve was evaluated with an emphasis on the particles retained within the sieves 2.36 and 9.5 mm as recommended by Shilstone in 1990 [13]. Average Δk was plotted against ISA intervals, then grouped on the MCFC. The objectives of such analyses were: to identify potential low Δk matching to respective ISA content; and to investigate correlations between low Δk and MCFC zones. No adjustments on the WF were required because concrete mixtures were not under evaluation in this phase of the research program.

4.1 Packing Variation and Intermediate-Sized Particles

An experimental approach was adopted in this study to identify how k of Southern U.S. limestone and silica sand correlate to ISA contents in aggregate blends. Results can add to the existing knowledge on concrete technology. Table 6 shows Δk and ISA percentages for each blend. Outcomes of 96 tests (Fig. 9) were grouped in three intervals determined by overall and localized gradation resemblance indicated that when ISA was between 25 and 27 % by weight, the average Δk was 1.7 %. For ISA between 17 and 22 %, the average Δk was 5.9 %, while blends with ISA within 28 and 29 % displayed an average Δk of 9.1 %. Results indicated that aggregate blends that contain 25 to 27 % of particles within sieves 2.36 and 9.5 mm presented the lowest variation between kr and kv. Thus, this range might be considered as optimal.

4.2 Intermediate-Sized Particles And MCFC

On the one hand, aggregate blends plotting on the MCFC's Zone II are thought to provide better consistency to Portland cement concrete. On the other hand, the farther the blend plots from the center of the WB, the lower the concrete slump is expected to be. Thus, this study focused on the influence that ISA could make on the aggregate gradation, and its effects on the concrete consistency prediction. Table 6 and Fig. 10 show that most aggregate blends with ISA content between 25 and 27 % by weight fell within Zone II. Blends B5 (ISA = 25 %), B6 (ISA = 26 %), and B7 (ISA = 27 %) plotted near the center of WB. Optimized blend B6 fell right at the center of the WB. Meanwhile, aggregate blends B1, B2, B3 and B4 (average ISA = 19%) plotted on Zone IV, whereas B8, B9, and B10 (average ISA = 28 %) plotted near the Zone II-IV edge.

Table 6 Summary of Test Results.

Blend	kr	kv	ISA, %	Δk, %	MCFC
B1	0.736	0.775	17.4	5.3	Zone IV
B2	0.722	0.791	19.2	9.6	Zone IV
B3	0.748	0.772	19.8	3.2	Zone IV
B4	0.722	0.763	21.1	5.7	Zone IV
B5	0.741	0.745	25.4	0.5	Zone II
B6	0.727	0.759	26.2	4.4	Zone II
B7	0.734	0.735	27.2	9.5	Zone II
B8	0.729	0.798	26.7	0.1	Zone IV
B9	0.733	0.823	28.6	12.3	Zone II
B10	0.747	0.788	29.0	5.5	Zone II

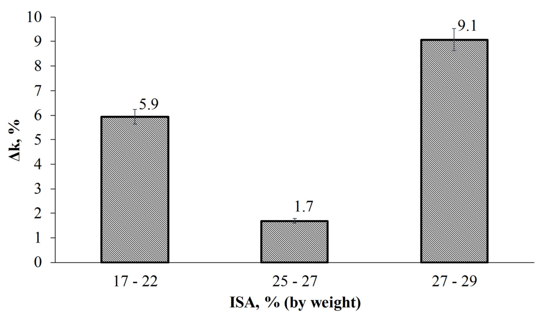

Fig. 9 Variation Among Dry-Rodded and Vibrated Aggregate Packing for Different Intermediate-Sized Aggregate Contents.

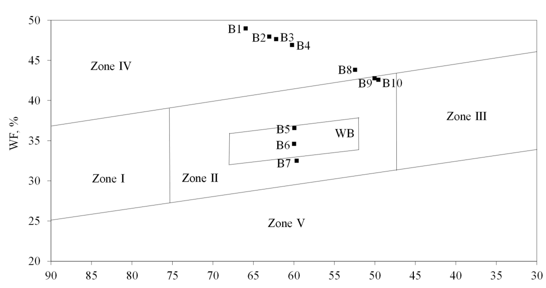

Fig. 10 Aggregate Blends Grouped on the Modified Coarseness Factor Chart (MCFC).

The results showed that aggregate blends containing 25 to 27 % by weight of particles retained between sieves 2.36 and 9.5 mm plotted within the Zone II of the MCFC, explicitly surrounding the WB, which is thought to provide better consistency to Portland cement concrete.

V. CONCLUSIONS

This study provides a theoretical and experimental analysis of the influence of intermediate-sized aggregate particle (ISA) content on dry-rodded (kr) and vibrated aggregate packing (kv), as well as on the Portland cement concrete consistency predictability through the Modified Coarseness Factor Chart (MCFC). The results obtained add to the knowledge gap addressing Southern U.S. limestone and silica sand.

The primary findings are:

• Aggregate blends containing 10 to 11 % IA by weight, which are equivalent to 25 to 27 % ISA content by weight of the aggregate, presented the lowest Δk (1.7 %). A low Δk can represent an overall low variability of the concrete consistency between design, production, and placement. Mixtures within this IA ranges can be considered optimal.

• Aggregate blends with 25 to 27 % ISA content by weight plot within the Zone II of the MCFC, which is thought to produce better workability to Portland cement concrete due to the gradation enhancement and lower fine-coarse aggregate friction.

Based on these findings, the conclusion is that the addition of an appropriate commercially available standard intermediate aggregate content may provide an adequate intermediate-sized aggregate particle content that can enhance the aggregate gradation and increase the predictability of the aggregate packing and Portland cement concrete consistency.

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