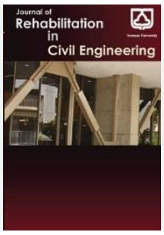

Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

DADmax/NADmax Ratio: Criterion for the Production and Selection of Demolition Aggregates with Low-Water Absorption

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ARTICLE INFO

Article history:
Received: 20 June 2023
Revised: 02 March 2024
Accepted: 30 April 2024

Keywords:
Demolition aggregates;
Natural aggregates;
Quality indicator;
DAD_{max}/NAD_{max} ratio;
Water absorption capacity.

ABSTRACT

The use of demolition aggregates (DAs) in second-generation concretes is an important issue, as they often have high water absorption, which affects the workability and durability of the cementitious materials incorporating them. This makes their direct use in structural concrete impossible. Previous studies have focused on downstream interventions aimed at improving the quality of DAs, such as eliminating old mortar (OM) adhered to natural aggregates (NAs) or limiting its absorption capacity. However, these approaches have proven to be expensive, time-consuming, and, for some, have health consequences. Our objective was to produce DAs suitable for use in structural concrete and to develop a simple, economical, and safe technique to generate good-quality DAs. We designed an upstream intervention based on the measurement of water absorption as a quality indicator. Seven ordinary concretes served as parent concretes (PCs), and after 28 days of maturation, the PC specimens were divided with a metal mass and then separated into ten different subfractions using standardized sieves. Three representative samples per subfraction were subjected to a twenty-minute water absorption evaluation, resulting in seventy arithmetic averages over 210 trials. Fractions (3/8), (8/16), and (16/25) were produced by clustering DA subfractions while emulating the granular distributions of NAs. The calculation of the DA fractions' water absorption was done based on the individual measurements obtained earlier. In the end, 21 average values were emerged. The maximum diameter of each DA (DAD_{max}) was related to that of the NA of its parent concrete (NAD_{max}), making it easier to distinguish between the most and least absorbent DAs. The ratios of 0.8 for the DA sub-fractions and 1 for the reconstituted DA fractions corresponded to DAs with the lowest water absorption capacity. For the DA sub-fractions, the minimum values are 12% to 82% below the average values and 28% to 89% below the maximum values. Similarly, DA fractions reconstituted from DA sub-fractions of the same PC showed a decrease in minimum values of 21% to 43% compared to average values and 31% to 58% compared to maximum values. Selecting the least absorbent DA sub-fractions without taking the PC into account resulted in a further reduction of 4% to 7% compared with the minimum values. The DAD_{max}/NAD_{max} ratio can therefore be used as a production and selection criterion for demolition aggregates.

E-ISSN: 2345-4423

How to cite this article:
Akroum, K., & Mezghiche, B. (2024). DADmax/NADmax Ratio: Criterion for the Production and Selection of Demolition Aggregates with Low-Water Absorption. Journal of Rehabilitation in Civil Engineering, 12(4), 1-19. https://doi.org/10.22075/jrce.2024.31002.1870

1. Introduction

The research conducted by de Larrard et al. and Gangu, S. K. [1,2], emphasizes the necessity of recycling waste from construction and public works to reduce the anthropogenic footprint. With a target set to recycle 70% of European waste by 2020, the recovery of demolished concrete aggregate (DAs) has garnered significant interest as a potential substitute for natural aggregates (NAs). [3,4]. However, the high-water absorption of DAs, influenced by the presence of old mortar (OM) detached or adhering to NAs, has posed a challenge to this substitution [5–7]. Hani Mokbel and Zhaoa et al. have established a correlation between the size of DAs (Demolition Aggregates) and their water absorption capacity. Specifically, the finest aggregates have been found to exhibit the highest water absorption capacity [8,9]. Kang et al. [10,11] discovered a link between the rise in DAs' (Demolition Aggregates') compressive strength and the increment in their size, which resulted from a decrease in old mortar (OM) content. Sánchez de Juan et al. and Hemmati Pourghashti, H. et al. [12,13] have reported that the old mortar (OM) content in the 4/8 mm fraction of DAs (Demolition Aggregates) ranges from 33% to 55%, while it ranges from 23% to 44% in the 8/16 mm fraction. To prevent excessive water absorption, it is recommended that DAs (Demolition Aggregates) for structural concrete should not contain more than 44% old mortar (OM). If the OM content exceeds this threshold, the water absorption of DAs may exceed 8%. To address this issue, researchers have explored two main approaches: mortar-gravel separation techniques (mechanical, chemical, physical, thermomechanical, etc.) and specific old mortar (OM) treatments (pre-saturation, pre-wetting, accelerated carbonation, using silane-based water repellents, etc.) [14–25]. In all instances, these strategies whether they involve separating mortar from gravel or treating old mortar, were implemented during the final stages of Demolition Aggregates (DAs) production [26–40]. However, according to S. Braymand and Yin Jinming, these methods carry costs, require time, and pose potential health risks for certain applications [41,42]. According to Jang, H. et al, [43] some treatments, such as hydrochloric acid (HCl) solutions, have an extreme level of aggressiveness, capable of disintegrating limestone aggregates during application. This characteristic requires meticulous attention when selecting appropriate methods because of the potential risks associated with this strong chemical. Within this research, we aimed to examine the effect of aggregate size, specifically looking at the ratio (DAD_{max}/NAD_{max}) of the maximum size of demolition aggregate (DAD_{max}) to that of natural aggregate (NAD_{max}) of the parent concrete, and to elucidate the correlation between this ratio and the water absorption capacity of the resulting material. Gravels intended for the manufacture of concrete are generally sold on the Algerian market in fractions 3/8, 8/16 and 16/25 (mm). Depending on the element to be produced (structural, decorative or other), one, two or three of these fractions are used in the concrete formulation. Which makes 7 gravel combinations possible. The latter were translated in this work into 7 types of parent concrete, among which we find binary, ternary and quaternary with granular skeletons that are continuous for some and discontinuous for others. This made it possible to study a variety of concretes. The sub-fractions chosen are based on the standardized sieves available at the laboratory level, of which there are 10. Each test is repeated 3 times and the average is calculated. Which gives a total of 210 values reduced into 70 average values. The parent concretes (PCs) were produced in a laboratory setting, and the maximum diameter of the Natural Aggregates (NAs) (NAD_{max}) was predetermined. If the PC is unknown, a visual examination is required to determine the NAD_{max}. The Demolition Aggregates (DAs) were sorted into sub-fractions based on their known maximum diameter (DAD_{max}), and their water absorption was measured for 20 minutes, with the DAD_{max}/NAD_{max} ratio serving as a determining factor. As per Zhaoa et al. [44], there is a strong correlation between the old mortar (OM) content in Demolition Aggregates (DAs) and their water absorption, with higher OM levels resulting in increased water absorption. By analyzing the water absorption data, a threshold ratio of DAD_{max}/NAD_{max} was determined to generate sub-fractions of Demolition Aggregates (DAs) containing a minimum amount of adherent mortar (OM). The sub-fractions were reclassified into (3/8), (8/16), and (16/25) fractions, aligning with the particle size distribution of the Natural Aggregates (NAs). The water absorption over 20 minutes was then calculated based on the dominance of each sub-fraction. Additionally, a DAD_{max}/NAD_{max} threshold ratio was defined for the (3/8), (8/16), and (16/25) fractions. Before the crushing process, the careful selection and management of Parent Concrete (PC) compositions, tailored to the desired Demolition Aggregate (DAs) fraction, constitutes an insightful upstream intervention.

2. Materials and experimental procedures

2.1. Materials

A CEM II A/42.5 grade Portland cement sourced from the Hadjar-Soud cement plant in Annaba, Algeria, served as the binding agent within the Parent Concrete (PC) formulations. This hydraulic binder comprises around 12% limestone and 74% clinker [45]. For cement hydration purposes, tap water was utilized [46]. As fine aggregates, naturally occurring alluvial sand was incorporated. Two types of coarse aggregates were applied: Natural Aggregates (NAs) derived from limestone rocks and Demolition Aggregates (DAs). Natural aggregates (NAs) were divided into three distinct size fractions: 3/8 (millimeters), 8/16 (millimeters), and 16/25 (millimeters). These fractions possess a specific gravity of 2.60 g/cm³, an apparent density of 1.65 g/cm³, a water absorption rate of 1.12%, and a Los Angeles coefficient of 23. In the assessment of water absorption, DAs (Demolition Aggregates) were segmented into the following sub-fractions for measurement: (2/3.15), (3.15/4), (4/5), (5/6.3), (6.3/8), (8/10), (10/12.5), (12.5/16), (16/20), and (20/25) millimeters. This detailed fractionation allows for a comprehensive analysis of water absorption characteristics across a range of particle sizes, providing valuable insights for various industrial and scientific applications. To maintain consistency with the initial natural aggregate (NA) samples, three new fractions: (3/8), (8/16), and (16/25) mm were reconstructed while preserving the same particle size distribution. The resulting demolition aggregates (DAs) exhibited a specific gravity ranging from 2.28 g/cm³ to 2.40 g/cm³, an apparent density varying between 1.14 g/cm³ and 1.40 g/cm³, a water absorption level of 1.30% to 8.7%, and a Los Angeles coefficient falling between 28 and 36. Figure 1 illustrates the gradation curves of the NA fractions (3/8), (8/16), and (16/25) mm used in this investigation.

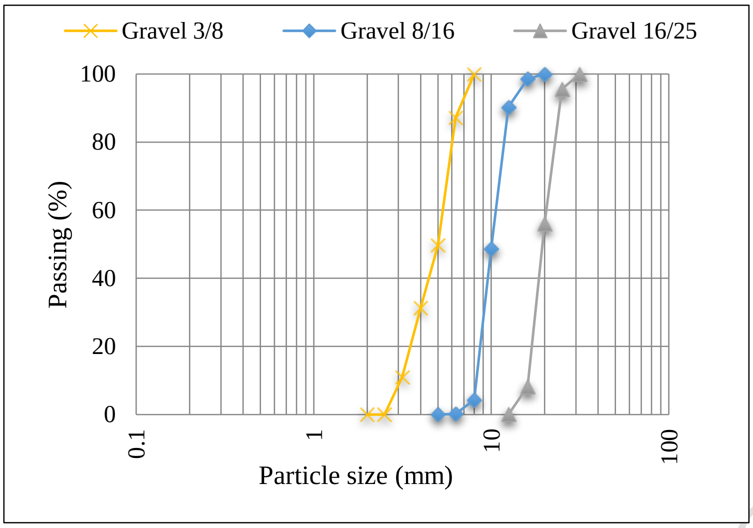

Fig. 1. Gradation curves of NAs and Das.

2.2. Experimental procedures

2.2.1. Formulation method of the parent concretes

Ordinary concrete specimens (PCs) were fabricated in the laboratory utilizing the DREUX-GORISSE mixing technique. [47]. Achieving the desired workability and strength criteria of concrete involves determining the optimal mixture of aggregates, cement, and water content. The predefined data used for this analysis includes the average compressive strength at 28 days, cement class, workability, maximum aggregate size, density of various aggregates, compactness, clamping intensity, and fineness modulus of the sand. To specify the different proportions of aggregates in absolute volume, draw a schematic granular reference curve. Once the aggregate density is determined, weight dosages can be calculated. Finally, conduct tests on the concrete and make any necessary experimental corrections to the formula. By using one, two, or three NA fractions between (3/8), (8/16), and (16/25), seven types of concrete have been developed: three binaries (PC1, PC2, and PC3), three ternaries (PC4, PC5, and PC6), and one quaternary (PC7). These compositions produce concrete of a quality similar to that of most Algerian manufactured concretes. [48,49] and ancient monuments which are on the verge of extinction, threatened by imminent demolition. PC1, PC4, and PC7 exhibit a continuous granular skeleton, while the remaining types are discontinuous. The mixing proportions of the PCs are provided in Table 1.

2.2.2. Mixing plan

After determining the concrete component proportions and weighing them, the dry aggregates and cement were sequentially added to a 35-liter concrete mixer, followed by 2 minutes of dry mixing. Subsequently, all the mixing water was added without stopping the mixer, and wet mixing was carried out for an additional 2 minutes, resulting in a total mixing time of 4 minutes. The fresh concrete was immediately poured after the mixing process. Cubic molds (10 cm on each side) were filled with concrete in two layers, vibrated for 30 seconds each, and then cured under laboratory conditions at a relative humidity of 75% and a temperature of 22ºC. After being left in their molds in open air for 24 hours, the samples were demolded, labeled, and stored in water tanks for 28 days according to standard NF P 18-405.[50].

2.2.3. Workability

The slump of all PC types was maintained at 7±2 cm, as per standard guidelines [51]. Table 1 provides a summary of the composition, water-to-cement ratio (W/C), and density of the parent concrete for each PC type.

Table 1. Parent concrete composition.

Designation	Unit	Proportioning of components in parent concrete						
		PC1	PC2	PC3	PC4	PC5	PC6	PC7
Cement	kg/m^3	400.000	398.310	360.290	398.310	360.290	360.290	360.290
Water	liter/m^3	200.000	207.120	194.560	207.120	194.560	194.560	194.560
Silicious Sand	kg/m^3	503.250	605.071	650.072	466.770	527.085	579.790	456.807
NA 3/8	kg/m^3	1221.220	-	-	269.690	383.720	-	219.270
NA 8/16	kg/m^3	-	1168.652	-	1042.800	-	383.720	292.360
NA 16/25	kg/m^3	-		1151.150	-	895.342	840.520	840.520
W/C	-	0.50	0.52	0.54	0.52	0.54	0.54	0.54
Density	kg/m^3	2324.470	2379.153	2356.072	2384.690	2360.997	2358.880	2363.807

2.2.4. Preparation of specimens

To produce high-quality concrete specimens, we fabricated 105 parent concrete (PC) samples with dimensions of 10×10×10 centimeters according to French standard NF P18-404 and European norm NF EN 12390-1. [52,53]. After conservation, we performed compression tests, which yielded a compressive strength range between 25.41 and 42.38 megapascals (MPa).

2.2.5. Preparation of demolition aggregates

After 28 days, the specimens were taken out of the water, allowed to dry in the open air, and then broken into pieces using a metal mass. The concrete pieces were sized to pass through the inputting mouth of the jaw crusher, with the distance between the jaws set according to the maximum aggregate size to be produced. The specific jaw crusher used is depicted in Figure 2.

Fig. 2. Jaw crusher.

Crushed materials were manually shaken through a succession of standardized sieves. Figure 3 illustrates various sizes and types of crushed demolition aggregates. By the standardized screening procedure depicted in our experiment (as detailed in Section 2.1. Materials), these materials were passed through sieves arranged in descending order based on their mesh sizes from the largest to the smallest.

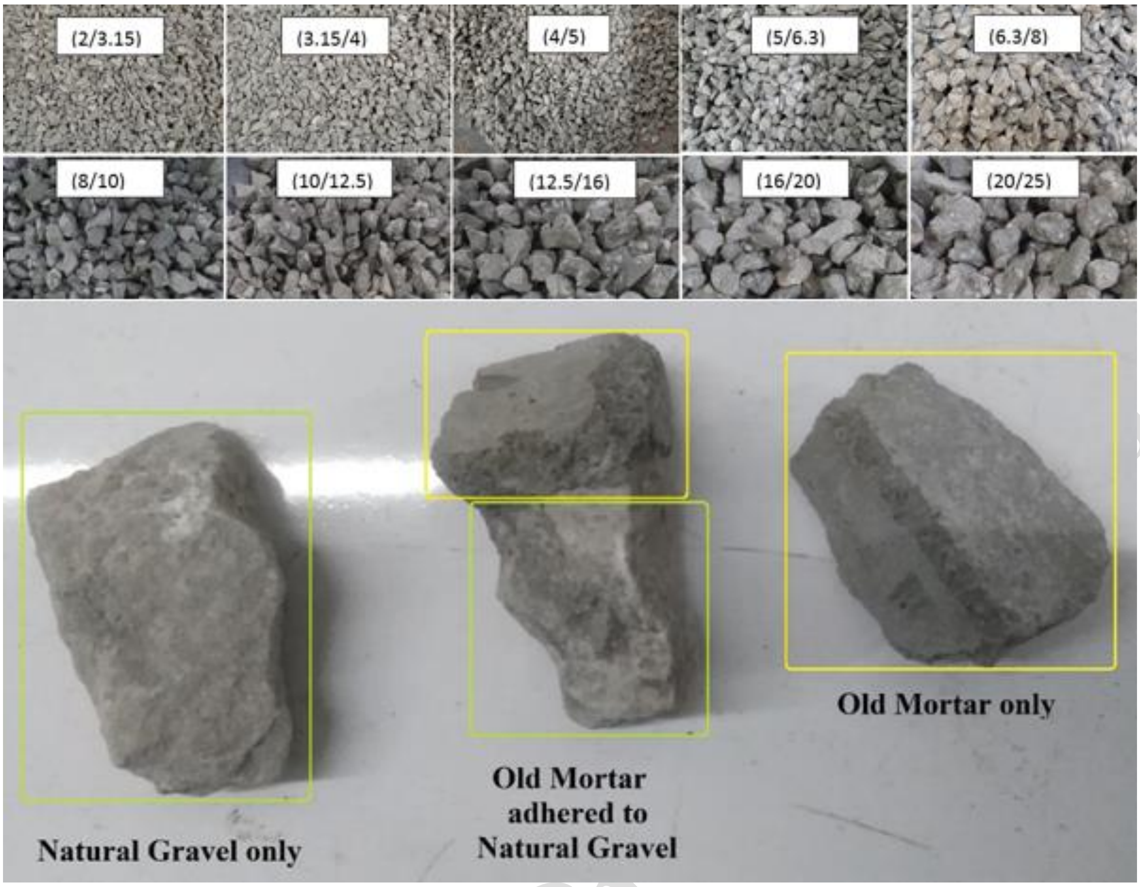

Fig. 3. Sizes and types of the crushed Das.

DAs with diameters greater than 25 mm were re-crushed and re-sieved. Any DAs with a diameter of less than 2 mm were discarded. The particulate matter remaining on each sieve was collected separately and dried in an oven until a constant mass was achieved. This process was conducted to obtain sufficient quantities of dry DA sub-fractions, specifically: (2/3.15), (3.15/4), (4/5), (5/6.3), (6.3/8), (8/10), (10/12.5), (12.5/16), (16/20), and (20/25), for the subsequent water absorption test.

2.2.6. Water absorption

The high water absorption of DAs has a significant impact on the workability of concrete, making it the most important property affected [54]. As noted by Y. L. Kun Liang et al. [55], the water absorption of DAs increases rapidly during the early stages. During the first 10 minutes, DAs reach approximately 90% of their water absorption capacity. Subsequently, DAs continue to absorb water at a slower rate until they reach saturation. Zhenhua Duan A. et al. [56] established a correlation between water absorption during the early stage and water absorption over 24 hours. The early phase can serve as an indicator of 24-hour water absorption, and vice versa. On this basis, and to save time due to the large number of samples, this study was limited to water absorption after 20 minutes only. After drying the DA subfractions in an oven at 110 ± 5 °C, until a constant mass, they were weighed and then immersed in tap water at 20 ± 2 °C. After 20 minutes, they were taken out of the water, wiped with a cloth to get a dry surface, and then weighed again. These steps are illustrated in Figure 4.

Fig. 4. Water absorption test steps.

The water absorption testing was performed on three specimens from each of the 70 DA sub-fractions by NF EN 1097-6 [57]. The water absorption determination was made using equation (1):

$$abs_i=100x(m_h-m_d)/(m_d) \quad (1)$$

where “abs_i” represents the percentage of water absorbed, “m_h” denotes the mass of the sample after immersion, and “m_d” refers to the initial mass of the dry sample. The results were reported as mean values.

2.2.7. Reconstitution of the gravel fractions

The (d/D) sub-fractions, where "d" represents the small particle diameter and "D" represents the large, were combined to form three fractions: (3/8), (8/16), and (16/25) with the same particle size distribution as the NAs. The mass of (d/D) corresponds to the refusal particular (ai) of the d mesh sieve, and the absorption after 20 minutes is then calculated.

The search algorithm is as follows:

- Preparation of parent concretes.
- Storage in water for up to 28 days.
- Size reduction with a metal mass.
- Crushing.
- Sieving and sub-fractionation ((2/3.15), (3.15/4), (4/5), (5/6.3), (6.3/8), (8/10), (10/12.5), (12.5/16), (16/20) and (20/25)).
- Rejection of the agglomerates less than 2 mm.

- Repetition of the previous steps (starting from crushing) for the particles larger than 25 mm.
- Oven drying to constant mass.
- Measurement of the water absorption of the sub-fractions after 20 minutes.
- Reconstitution of gravel fractions: ((3/8), (8/16) and (16/25)).
- Calculation of the water absorption of the reconstituted gravel fractions after 20 minutes.

The diagram of the process is illustrated in Figure 5.

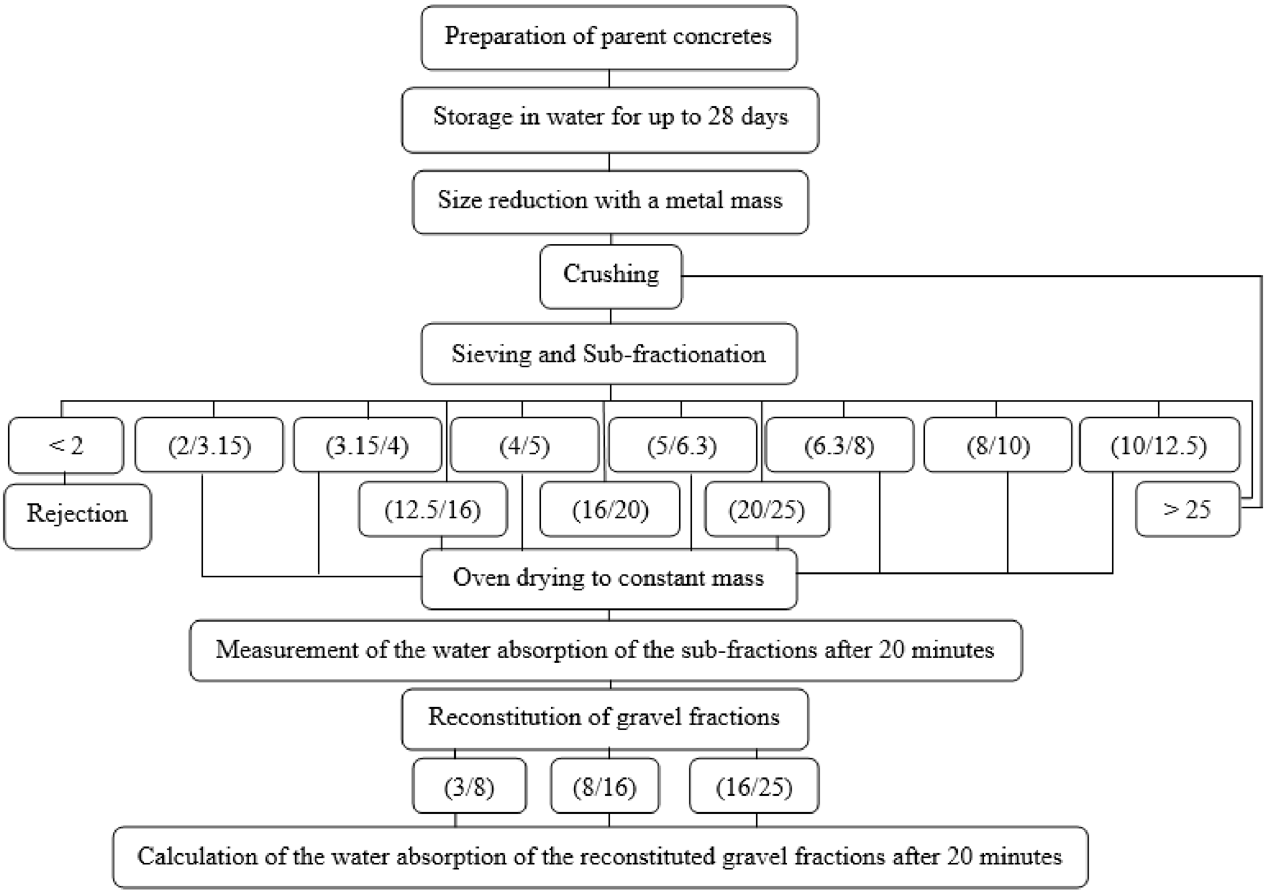

Fig. 5. Procedure for the preparation of DAs and quantification of water absorption.

The time conditions are summarized in Table 2.

Table 2. Time and location conditions for the tests.

Operation	Time	Temperature	Location	Device/Tool	Standards
PC manufacturing	14 hours	20±2 °C	Laboratory setting	35-liter concrete mixer	NF P18-405
Curing	28 days	20±2 °C	Laboratory setting	Water tank	NF P18-404
Size reduction	4 hours	20±2 °C	Laboratory setting	Metal mass	-
Crushing	3 hours	20±2 °C	Laboratory setting	Jaw crusher	-
Fractionation	7 days	20±2 °C	Laboratory setting	Sieves	-
Oven drying	48 hours	105±5 °C	Laboratory setting	Oven	-
Dry weighing	10 seconds	20±2 °C	Laboratory setting	Precision Scale 0.1 gr	NF EN 1097-6
Water immersion	20 minutes	20±2 °C	Laboratory setting	water container	NF EN 1097-6
Dewatering	10 seconds	20±2 °C	Laboratory setting	Sieve	NF EN 1097-6
Surface drying	20 seconds	20±2 °C	Laboratory setting	Dry cloth	NF EN 1097-6
Wet weighing	10 seconds	20±2 °C	Laboratory setting	Precision Scale 0.1 gr	NF EN 1097-6

The water absorption properties of the selected DAs were investigated. The DAs were divided into sub-fractions based on their maximum diameter (DAD_{max}) and subjected to a 20-minute water absorption test according to the NF EN 1097-6 standard [57]. The results obtained from the water absorption tests were analyzed to determine the relationship between the DAD_{max} and the water absorption behavior of the DAs. The analysis aimed to define a DAD_{max}/NAD_{max} threshold ratio to produce DA sub-fractions with minimal adherent mortar (OM) content, thereby improving the mechanical performance of the resulting concrete mixtures. Three DA sub-fractions (3/8), (8/16), and (16/25) were created to match the particle size distribution of the NAs. The water absorption characteristics of these sub-fractions were compared to evaluate their suitability for use in concrete production. The investigation included the development of six concrete mix designs incorporating varying amounts of the three DA sub-fractions, along with NAs, to assess the effect of the DA sub-fractions on the mechanical properties of the resulting concrete mixtures.

3. Results and discussion

3.1. Water absorption

As the size of the demolished aggregates (DA) decreases, water absorption increases, which aligns with the results reported by Kim Jeonghyun [58]. This trend is visually depicted in Figures 6 and 7, illustrating the water absorption after 20 minutes of the DA's sub-fractions and reconstituted fractions, respectively.

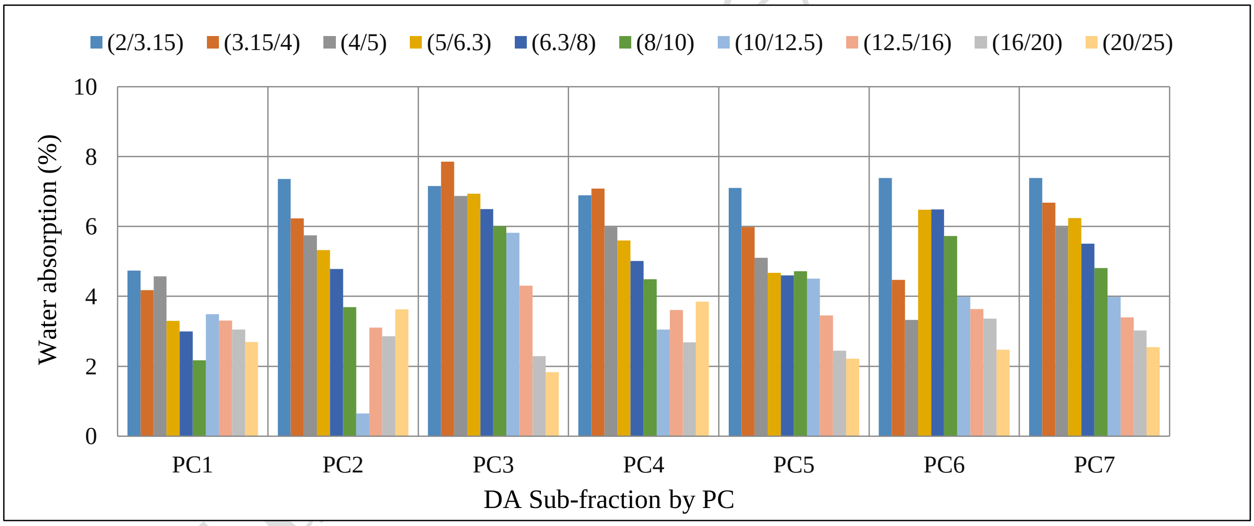

Fig. 6. Water absorption after 20 minutes of DA sub-fractions (%).

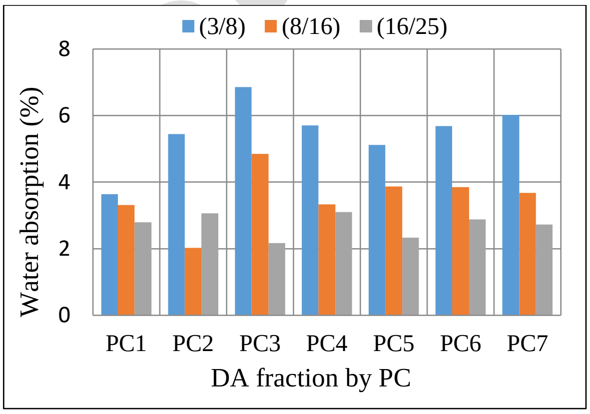

Fig. 7. Water absorption after 20 minutes of DA reconstituted fractions (%).

The water absorption of each DA sub-fraction significantly influences the overall water absorption of the respective DA fraction, as indicated in Table 3 and Table 4. This influence varies based on the dominance of the DA sub-fraction, which is determined by its specific refusal percentage obtained from the granulometric analysis, as shown in Table 5. The water absorption of the DA fraction was calculated using equation (2).

$$abs = (1/100) \text{ x } \sum (abs_i \text{ x } a_i) \quad (2)$$

where "abs" represents the water absorption of a DA fraction, "abs_i" denotes the water absorption of a DA sub-fraction, and "ai" refers to the specific refusal percentage of a sub-fraction.

Table 3. Water absorption of DA aggregate sub-fractions after 20 minutes.

(d/D)	Parent concretes Water absorption after 20 minutes (%)						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
(2/3.15)	4.74	7.36	7.16	6.89	7.10	7.39	7.39
(3.15/4)	4.18	6.23	7.85	7.08	5.98	4.47	6.68
(4/5)	4.57	5.75	6.87	5.98	5.10	3.33	5.98
(5/6.3)	3.30	5.32	6.94	5.60	4.67	6.48	6.24
(6.3/8)	3.00	4.78	6.50	5.01	4.60	6.49	5.51
(8/10)	2.17	3.69	6.01	4.49	4.72	5.73	4.81
(10/12.5)	3.49	0.65	5.82	3.05	4.51	3.99	3.99
(12.5/16)	3.31	3.11	4.31	3.61	3.45	3.64	3.40
(16/20)	3.05	2.86	2.29	2.68	2.45	3.36	3.02
(20/25)	2.69	3.63	1.83	3.85	2.22	2.47	2.55

Table 4. Water absorption of DA reconstituted fractions after 20 minutes.

(d/D)	Parent concretes Water absorption after 20 minutes (%)						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
(3/8)	3.64	5.44	6.85	5.7	5.12	5.68	6.02
(8/16)	3.31	2.02	4.86	3.31	3.88	3.86	3.69
(16/25)	2.91	3.22	2.25	3.27	2.43	2.99	2.84

Table 5. Refusal particular of NA and DA sub-fractions.

(d/D)	Refusal particular a_i (%)		
	(3/8)	(8/16)	(16/25)
(2/3.15)	9.39	5.44	6.85
(3.15/4)	10.93		
(4/5)	20.40		
(5/6.3)	18.46		
(6.3/8)	37.41	0.18	
(8/10)	3.41	4.11	
(10/12.5)		44.42	
(12.5/16)		41.59	8.23
(16/20)		8.30	47.79
(20/25)		1.40	43.98

The reconstitution of DA fractions from the DA sub-fractions follows an inverse relationship with respect to size and water absorption. Maximal water absorption values of the DA sub-fractions fall within the range of [3.36%; 7.85%], while mean values lie between [2.75%; 6.86%] and minimum values span from [0.65%; 4.74%]. Minimum values represent 12% to 82% lower than mean values and 28% to 89% lower than maximal values. Figure 8 demonstrates the maximum, average, and minimum values of water absorption for DA sub-fractions corresponding to their parent concretes (PCs).

Reconstituting DA fractions based on their corresponding DA sub-fractions from the same parent concrete (PC) resulted in maximal water absorption values ranging from [3.27%; 6.85%], average values ranging from [2.84%; 5.49%], and minimal values ranging from [2.02%; 3.64%]. The minimal values are 21% to 43% lower than the average values and 31%

to 58% lower than the maximal values. Figure 9 illustrates the maximum, average, and minimum values of water absorption for reconstituted DA fractions corresponding to their parent concretes (PCs).

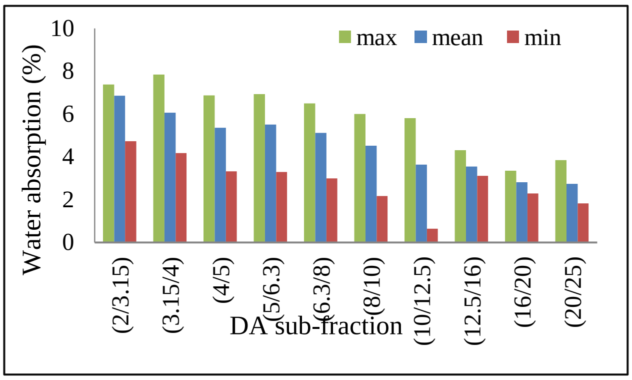

Fig. 8. Maximum, average and minimum values of water absorption of DA sub-fractions.

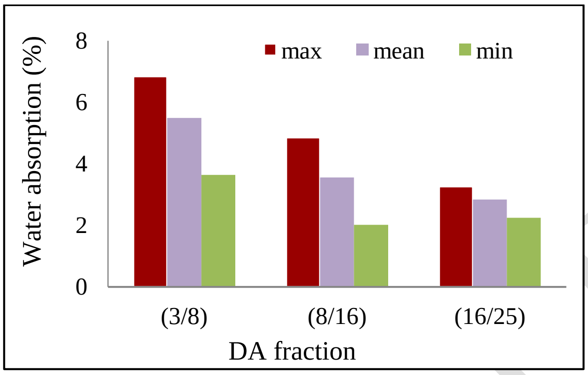

Fig. 9. Maximum, average and minimum values of water absorption of DA reconstituted fractions.

When selecting the least absorbent DA sub-fractions without accounting for the parent concrete (PC), the resultant minimum water absorption values fell within the range of [1.89%; 3.39%]. Compared to the minimum values derived from DA sub-fractions of the same parent concrete (PC), these values experienced a decrease of 4% to 7%. Figure 10 displays the contrast between the minimum water absorption values of the DA reconstituted fractions when the DA sub-fractions originate from the same PC (min) and when they stem from various PCs (min selected). The DA sub-fractions with the least water absorption values, without considering the parent concrete (PC), include (2/3.15), (3.15/4), (5/6.3), and (6.3/8) from PC1, (4/5) from PC6, (10/12.5) and (12.5/16) from PC2, and (16/20) and (20/25) from PC3. Figure 10 illustrates the contrast between the minimum water absorption values of the reconstituted DA fractions when the DA sub-fractions originate from the same parent concrete (PC) (min) and when they are selected from various PCs (min selected).

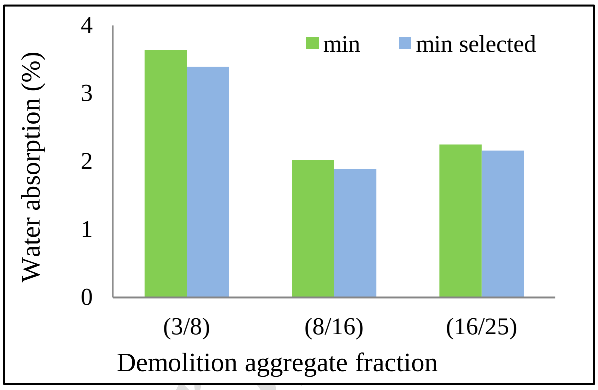

Fig. 10. Minimum water absorption values of the DA reconstituted fractions from the same PC (min) and selected from all the PCs (min selected).

The relationship between the maximum diameter of the DA sub-fraction (DAD_{max}) and the maximum diameter of the NA fraction of the parent concrete (NAD_{max}) allowed for easy differentiation between the most and least absorbent DA sub-fractions based on the DAD_{max}/NAD_{max} ratio. Figures 11 and 12 depict the water absorption after 20 minutes of DA sub-fractions and reconstituted DA fractions as a function of the DAD_{max}/NAD_{max} ratio. Water absorption is less than 4% when the DAD_{max}/NAD_{max} ratio is greater than 0.8 for DA sub-fractions and greater than 1 for DA reconstituted fractions. For lower values of the DAD_{max}/NAD_{max} ratio, water absorption decreases as the DAD_{max}/NAD_{max} ratio increases.

3.2. Statistical analysis

Two variables, namely "DA size" and "DA origin (parent concrete)", were analyzed to understand their individual impacts on the 20-minute water absorption of DA. Analysis of Variance (ANOVA) statistics [59] were employed to ascertain if each variable had a substantial effect on the 20-minute water absorption and to calculate the primary contributions of each variable towards total variation. Significantly, any factor with a significance level below or equivalent to 5% ($p \leq 0.05$) was deemed statistically relevant.

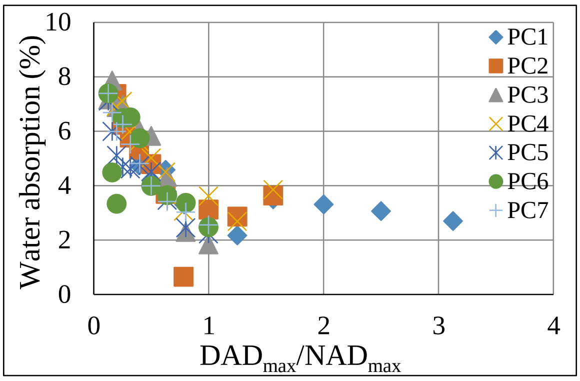

Fig. 11. Water absorption of DA sub-fractions after 20 minutes as a function of DAD_{max}/NAD_{max} ratio.

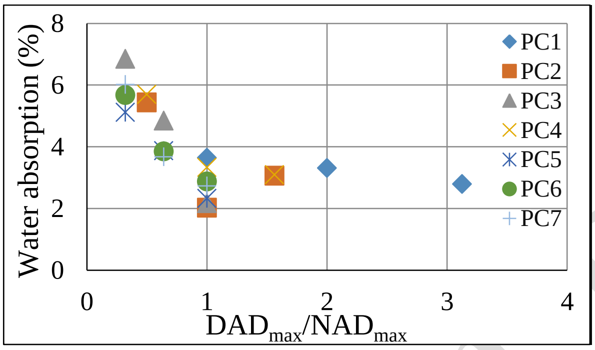

Fig. 12. **Water absorption of DA reconstituted fractions after 20 minutes as a function of DAD_{max}/NAD_{max} ratio.**

3.1.1. Statistical analysis of DA sub-fractions (d/D)

Tables 6 and 7 provide a summary and the results of the ANOVA single test for 20-minute water absorption with the independent variable "DA sub-fraction size." The test statistics in this case are highly significant (P-value = 3.71 E-10 < 0.05 and F = 11.38 > Fcrit = 2.04). Thus, it can be concluded that the "DA sub-fraction size (d/D)" significantly differentiates demolition aggregate sub-fractions in terms of 20-minute water absorption. The standard deviation values are relatively small around each mean, indicating that the population of results remains tightly clustered around the average.

Table 6. Summary of the ANOVA for 20 minutes-water absorption related to DA sub-fraction size.

Summary	Count	Sum	Average	Variance	SD
(2/3.15)	7	48.03	6.86	0.91	0.95
(3.15/4)	7	42.47	6.07	1.79	1.34
(4/5)	7	37.58	5.37	1.34	1.16
(5/6.3)	7	38.55	5.51	1.53	1.24
(6.3/8)	7	35.89	5.13	1.47	1.21
(8/10)	7	31.62	4.52	1.67	1.29
(10/12.5)	7	25.5	3.64	2.51	1.58
(12.5/16)	7	24.83	3.55	0.15	0.38
(16/20)	7	19.71	2.82	0.14	0.37
(20/25)	7	19.24	2.75	0.54	0.73

Table 7. Results of the ANOVA for 20 minutes-water absorption related to DA sub-fraction size.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	123,18	9	13,69	11,38	3,71E-10	2,04
Within Groups	72,19	60	1,20			
Total	195,37	69				

Tables 8 and 9 present a summary and the results of the ANOVA single test for 20-minute water absorption with the independent variable "DA sub-fraction origin." The test statistics in this case are insignificant (P-value = 0.176 > 0.05 and F = 1.55 < Fcrit = 2.25). Thus, it can be concluded that the "origin (PC)" does not significantly differentiate demolition aggregate sub-fractions in terms of 20-minute water absorption.

Table 8. Summary of the ANOVA for 20 minutes-water absorption related to sub-fraction origin.

Summary	Count	Sum	Average	Variance	SD
PC1	10	34.50	3.45	0.67	0.95
PC2	10	43.38	4.34	3.79	1.34
PC3	10	55.58	5.56	4.31	1.16
PC4	10	48.24	4.82	2.40	1.24
PC5	10	44.80	4.48	2.21	1.21
PC6	10	47.35	4.73	2,78	1.29
PC7	10	49.57	4.96	2.76	1.58

Table 9. Results of the ANOVA for 20 minutes-water absorption related to sub-fraction origin.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	25,16	6	4,19	1,55	0,18	2,25
Within Groups	170,20	63	2,70			
Total	195,37	69				

3.1.2. Statistical analysis related to DA fraction (d/D)

Tables 10 and 11 provide a summary and the results of the ANOVA single test for 20-minute water absorption with the independent variable "DA fraction size." The test statistics in this case are highly significant (P-value = 9.64 E-06 < 0.05 and F = 23.48 > Fcrit = 3.55). Thus, it can be concluded that the "DA fraction size" significantly differentiates demolition aggregate fractions in terms of 20-minute water absorption. The standard deviation values are relatively small around each mean, indicating that the population of results remains tightly clustered around the average.

Table 10. Summary of the ANOVA for 20 minutes-water absorption related to DA fraction size.

Summary	Count	Sum	Average	Variance	SD
(3/8)	7	38.45	5.49	0.96	0.98
(8/16)	7	24.92	3.56	0.72	0.85
(16/25)	7	19.06	2.72	0.12	0.35

Table 11. Results of the ANOVA for 20 minutes-water absorption related to DA fraction size.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	28.25	2	14.13	23.48	9.64 E-06	3.55
Within Groups	10.83	18	0.60			
Total	39.09	20				

Tables 12 and 13 present a summary and the results of the ANOVA single test for 20-minute water absorption with the independent variable "DA fraction origin (PC)." The test statistics in this case are insignificant (P-value = 0.95 > 0.05 and F = 0.25 < Fcrit = 2.85). Thus, it can be concluded that the "DA fraction parent concrete" does not significantly differentiate demolition aggregate fractions in terms of 20-minute water absorption.

Table 12. Summary of the ANOVA for 20 minutes-water absorption related to DA fraction origin.

Summary	Count	Sum	Average	Variance	SD
PC1	3	9.74	3.25	0.18	0.95
PC2	3	10.53	3.51	3.06	1.34
PC3	3	13.87	4.62	5.51	1.16
PC4	3	12.13	4.04	2.07	1.24
PC5	3	11.32	3.77	1.95	1.21
PC6	3	12.41	4.14	2.02	1.29
PC7	3	12.43	4.14	2.87	1.58

Table 13. Results of the ANOVA for 20 minutes-water absorption related to DA fraction origin.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.75	6	0.62	0.25	0.95	2.85
Within Groups	35.34	14	2.52			
Total	39.09	20				

3.1.3. Validation

Scale calibration

Scale calibration is performed using high-precision standard weights, in accordance with the manufacturer's recommendations and ASTM standard E898-20 [60], in its normal operating environment, covering its entire measuring range. The tolerance of the scale was determined by comparing actual weights with theoretical weights, using high-precision standard weights. The scale has undergone periodic visual inspection. No physical damage or other problems potentially affecting their performance were detected.

Laboratory Tests

The water absorption of a demolition aggregate (DA) is dominated by the rate of old mortar (OM) adhered to the natural aggregate (NA). It can vary according to the DA granular sub-fraction. Repeatability was carried out under the same conditions [61,62] on three selected DA sub-fractions: one of small size (2/3.15), one of medium size (8/10), and one of large size (16/20). The tests were performed in two different ways:

Three times in succession on the same test sample of the three DAs sub-fractions chosen.

Once on five different test samples per sub-fraction of the three DAs sub-fractions chosen.

The Standard deviation (SD) and the relative Standard deviation (RSD) are shown in tables 14 and 15

Table 14. Summary of water absorption measurements at 20 minutes obtained using the standard method for a single test sample.

DA Sub-fraction	Tests number	20-minutes water absorption	SD	RSD
(2/3.15)	3	8.64%	0.92%	10.68%
(8/10)	3	5.34%	1.41%	26.50%
(16/20)	3	3.67%	0.57%	15.45%

The results show an RSD of between 10.68% and 26.50% indicating a moderate level of dispersion around the average water absorption.

Table 15. Summary of water absorption measurements at 20 minutes obtained using the standard method at 5 different test points.

DA Sub-fraction	Tests number	20-minutes water absorption	SD	RSD
(2/3.15)	5	5.83%	1.79%	30.68%
(8/10)	5	3.86%	1.01%	26.19%
(16/20)	5	3.46%	1.05%	30.32%

The results indicate a moderate level of dispersion around the average water absorption, with an RSD ranging between 26.19% and 30.68%. However, when measurements are taken on different test points, the relative standard deviation increases considerably.

4. Conclusion

In conclusion, this experimental study aimed to reduce old mortar (OM) content in demolition aggregates (DAs) efficiently and cost-effectively, while mitigating production delays and health risks. Key findings from the research are as follows:

A ratio threshold of 0.8 for DA subfractions correlates with significantly reduced water absorption capacity, ranging from 12% to 82% below average values and 28% to 89% below maximum values.

A threshold ratio of 1 for DA fractions reconstituted from the same Parent Concrete (PC) subfractions results in DAs with notably low water absorption capacity, showing reductions of 21% to 43% compared to average values and 31% to 58% compared to maximum values.

Selecting DA subfractions based on water absorption capacity without considering the PC leads to an additional reduction of water absorption capacity by 4% to 7% compared to minimum values.

Determining the minimum size of DA before crushing should be guided by the DAD_{max}/NAD_{max} ratio threshold.

Optimal selection involves choosing subfractions with a DAD_{max}/NAD_{max} ratio of 0.8 for existing DA and reconstituting desired DA fractions from these selected subfractions.

The size of the DA significantly impacts water absorption within a short timeframe of 20 minutes.

In summary, this study introduces an innovative approach to enhancing the quality of DAs for structural concrete applications, promoting environmental sustainability in construction. The insights provided offer valuable guidance for optimizing DA production with reduced OM content, leading to cost savings, improved efficiency, and decreased health risks in construction practices

Abbreviations

PC: parent concrete.
NA: natural aggregate.
DA: demolition aggregate.
OM: old mortar.
NAD_{max}: maximum diameter of natural aggregate.
DAD_{max}: maximum diameter of demolition aggregate.
DAD_{max}/NAD_{max}: ratio of the maximum diameter of demolition aggregate to the maximum diameter of natural aggregate.
W/C: water-to-cement ratio.
abs_i: sub-fraction water absorption (%).
abs: fraction water absorption (%).
m_h: mass of the aggregate after 20 minutes of immersion (kg).
m_d: mass dry of the aggregate (kg).
d: diameter of the smallest grain of the aggregate.
D: diameter of the largest grain of the aggregate.
d/D: designation of the aggregate sub-fraction and fraction.
a_i: refusal particular of the "d" mesh sieve (%).
ANOVA: analysis of variance.
SD: standard deviation.
RSD: relative standard deviation.
DF: degree of freedom.
SS: sum of squares.
MS: mean of the squares.
F: ratio of the mean square between to mean squared Error.
P-value: ratio of the mean squares' treatment to the mean squares error.
Fcrit: critical ratio of the mean square between to mean squared Error.

Declaration of competing interest

The authors of this paper declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. This ensures that the research and its findings are unbiased and free from any external influence that could compromise the integrity of the study.

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