

Experimental Investigation on the Behavior of Recycled Concrete incorporating Date Palm Fibers

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ABSTRACT

Recently, the use of Recycled Aggregates (RA) and natural fibers as reinforcement in concrete has received increasing attention due to their ability to reduce environmental impact and promote sustainable, cost-effective construction. This study evaluates the mechanical and thermal properties of Date Palm Fiber-Reinforced Recycled Aggregate Concrete (DPFRAC), including compressive strength, flexural strength, and thermal conductivity. A total of nineteen mixes were tested with varying RA substitutions (0%–50% and 100%), Date Palm Fibers (DPF) additions (1%–3%), and combined modifications of DPF (1%–3%) and RA (10%–30%) to assess the synergistic effects. A Superplasticizer (SP) and a Modified Two-Stage Mixing Method (MTSMM) were employed to enhance concrete performance. The findings reveal that the modified mixing method improves compressive strength, especially for RA substitutions below 50%. Adding 2% DPF to concrete with 30% RA improves compressive and flexural strengths by 11.16% and 7.03%, respectively, compared to fiberless Recycled Aggregate Concrete (RAC), achieving a performance close to Natural Aggregate Concrete (NAC). Furthermore, thermal conductivity decreases by 18.27%, enhancing insulation properties. These findings highlight DPFRAC's dual functionality as a structural material with improved thermal efficiency, making it suitable for eco-friendly construction by reducing reliance on virgin materials and minimizing carbon footprints, particularly in arid regions where date palm waste is abundant.

Keywords-concrete; recycled aggregates; date palm fibers; two-stage mixing; mechanical properties; thermal conductivity

I. INTRODUCTION

Concrete, the backbone of modern infrastructure, is the world's most widely used construction material due to its

availability, ease of production, cost-effectiveness, and superior structural performance. Aggregates, accounting for 70-80% of concrete composition, are vital to its structural integrity. Global aggregate consumption reached an impressive 48 billion tons in

2015, with projections indicating a continued growth of more than 5% every five years [1]. To mitigate environmental impacts, the construction industry has increasingly turned to RA sourced from Construction and Demolition Waste (CDW), which generates 3 billion tons of waste annually across 40 countries [2]. Despite its environmental benefits, RA adoption remains limited due to its lower mechanical properties and variability in performance [3–7].

Extensive research [3–7] has systematically investigated the characteristics of RA and its effects on RAC. Several studies show that RA has a 3.34–18.66% lower density than NA [3, 8], while 100% RA substitution can reduce compressive and flexural strengths by up to 45.2% and 49.8%, respectively [6]. However, the findings in [9] suggest that using up to 20% RA replacement has minimal impact on strength, making it practical. A 30% replacement rate is often proposed as the optimal balance between sustainability and mechanical performance [7]. These findings, however, vary across studies due to differences in RA sources, treatment methods, and mix designs. Conversely, RAC has reduced thermal conductivity by up to 33% compared to NAC [10], primarily due to the increased micropores in RA acting as thermal barriers. This trade-off between mechanical and thermal performance underscores the need for innovative solutions to enhance RA viability. Researchers have proposed strategies to mitigate these limitations [11–12], including sequential mixing methods and fiber reinforcement. While metallic and synthetic fibers improve strength, their high carbon footprint conflicts with sustainability goals. Natural fibers, such as coconut or sisal [13], have garnered attention for their sustainable and eco-friendly characteristics. Recent research in biocomposites, such as *Posidonia oceanica* fibers in thermoplastics [14] and DPF in polylactic acid (PLA) matrices [15], demonstrates the potential of agricultural waste in materials.

Among natural fibers, DPF has shown promise in improving concrete properties. Research indicates that DPF can increase compressive strength by up to 16.2% [16], flexural strength by 17% [17], and reduce thermal conductivity by up to 35.5% [18]. However, most existing research focuses on DPF in conventional concrete [17–22], with a limited exploration of its synergy with RA in RCA [16, 23].

The current study aims to fill this research gap by evaluating the mechanical and thermal properties of DPFrac using an MTSMM. By investigating DPF impact on compressive strength, flexural strength, and thermal conductivity, this research aims to advance sustainable construction practices and promote the effective utilization of locally available resources.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

The concrete was produced using locally sourced materials from Tebessa, Algeria. The cement was CEM II/42.5 R, a high-quality composite Portland cement known for its exceptional strength. The rolled sand (0/5 mm) was utilized as Fine Aggregate (FA), with a specific density of 2150 kg/m³, a fineness modulus of 2.43, and a sand equivalent of 71.5%. The coarse aggregate includes NA, composed of crushed limestone

in 8/15 mm and 15/25 mm fractions, and RA, produced by crushing concrete elements from a previous experimental campaign, as illustrated in Figure 1, followed by sieving to achieve the target particle size distributions. Due to lower mechanical stress, this method can preserve the mechanical properties of the aggregates, particularly their strength and angularity. Figure 2 presents the sieve analyses of the used aggregates, and Table I summarizes the physical properties of the coarse aggregates.

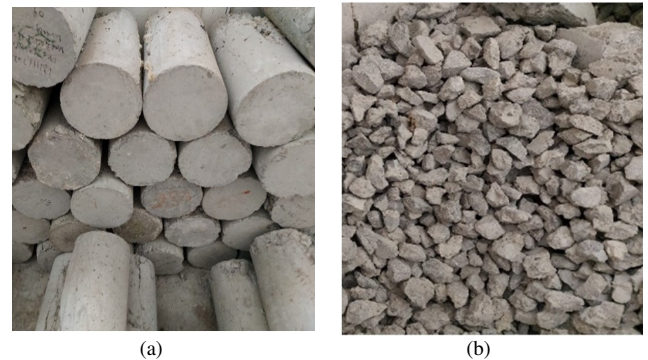


Fig. 1. (a) Concrete elements used, (b) obtained RA.

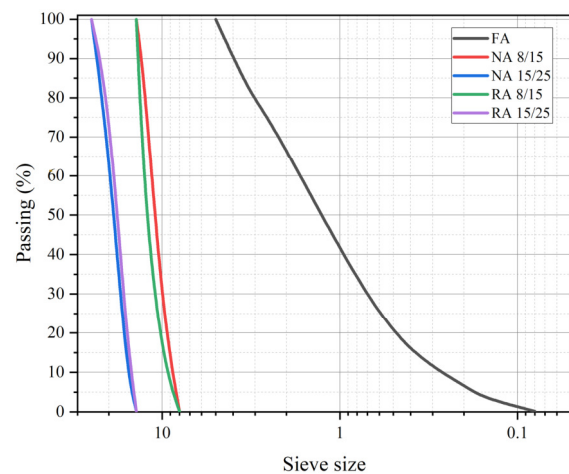


Fig. 2. Used aggregate gradation curves.

TABLE I. PHYSICAL CHARACTERISTICS OF COAST/COARSE AGGREGATES

| Type of coarse aggregate | | Bulk density (kg/m ³) | Specific density (kg/m ³) | Water absorption (%) |
|--------------------------|-------|-----------------------------------|---------------------------------------|----------------------|
| NA | 8/15 | 1402 | 2666 | 1.05 |
| | 15/25 | 1283 | 2721 | 1.21 |
| RA | 8/15 | 1072 | 2500 | 6.61 |
| | 15/25 | 1132 | 2589 | 4.84 |

Compared to NA, RA exhibited a reduction in relative density ranging from 4.8–6.23%. It also showed a 2-5 folds higher water absorption capacity, primarily due to the residual hydrated cement paste adhered to the RA surfaces, significantly increasing porosity.

DPF, used as reinforcement, were sourced from the *Deglet Noor* variety and collected from the oases of Doucen-Ouled Djellal, Algeria. The raw palm wood was mechanically processed using a wood planer to generate fibers of varying lengths with a maximum diameter of 3 mm, as portrayed in Figure 3. Tap water was utilized in the mixes, and an SP additive, Sika ViscoCrete TEMPO-12, based on acrylic copolymer, was added to improve workability and reduce water demand. The water/cement (w/c) ratio ranged from 0.51 to 0.57, depending on the mixes' RA and DPF content proportion.



Fig. 3. Processing of DPF: (a) raw petiole, (b) mechanical planing, and (c) final fibers.

RA and DPF were used in their raw state without any treatment, which reduces costs and environmental impact. This approach enables the assessment of their influence on the mechanical and thermal behavior of the concrete.

B. Concrete Mix Design

MTSMM was employed to optimize concrete properties. This approach was adapted from the two-stage mixing method proposed in [24], with further modifications to improve homogeneity and fiber dispersion while addressing potential workability issues caused by the high water absorption of RA and DPF. The key steps of this method are:

Step 1: The aggregates, cement, and, when applicable, fibers were dry-mixed for approximately 2 minutes to ensure uniform distribution. Then, half of the mixing water was added and mixed for another 2 minutes. Next, the SP, pre-diluted in a portion of the remaining water, was introduced into the mixture and blended for an additional minute. During this phase, the SP was employed as a rheological modifier by coating the RA and DPF, thereby improving the mobility of the cement paste around these absorbing materials.

Step 2: The remaining water was gradually added to ensure precise water demand control, optimize workability, and prevent oversaturation. Workability was assessed using slump tests, with adjustments in SP dosage or water content to maintain slump values within the target range.

Nineteen different mixes were prepared employing the Dreux-Gorisse method [25] to determine the optimal sand-to-aggregate ratio based on standard reference grading curves. The concrete mixtures were formulated concerning the

subsequent variables: concrete containing only NA (NAC), substituting NA with RA at volumetric ratios of 10%, 20%, 30%, 40%, 50%, and 100% (RACx), incorporation of DPF into NAC at cement mass ratios of 1%, 2%, and 3% (NACFy), simultaneously replacing NA with RA at volumetric ratios of 10%, 20%, and 30%, combined with adding DPF at cement mass ratios of 1%, 2%, and 3%, (RACxFy). The specific mix proportions for each configuration are detailed in Table II.

TABLE II. DETAILS OF MIX PROPORTIONS (kg)

| Mixture | NA 8/15 | NA 15/25 | RA 8/15 | RA 15/25 | DPF | W/C |
|---------|---------|----------|---------|----------|------|------|
| NAC | 414.0 | 740.2 | - | - | - | 0.51 |
| RAC10 | 372.6 | 666.2 | 38.90 | 70.40 | - | 0.51 |
| RAC20 | 331.2 | 592.2 | 77.60 | 140.9 | - | 0.51 |
| RAC30 | 289.8 | 518.2 | 116.4 | 211.3 | - | 0.51 |
| RAC40 | 248.4 | 444.1 | 155.2 | 281.7 | - | 0.51 |
| RAC50 | 207.0 | 370.1 | 194.1 | 352.1 | - | 0.53 |
| RAC100 | - | - | 388.1 | 704.3 | - | 0.57 |
| NACF1 | 414.0 | 740.2 | - | - | 3.5 | 0.51 |
| RAC10F1 | 372.6 | 666.2 | 38.90 | 70.40 | 3.5 | 0.51 |
| RAC20F1 | 331.2 | 592.2 | 77.60 | 140.9 | 3.5 | 0.51 |
| RAC30F1 | 289.8 | 518.2 | 116.4 | 211.3 | 3.5 | 0.51 |
| NACF2 | 414.0 | 740.2 | - | - | 7.0 | 0.51 |
| RAC10F2 | 372.6 | 666.2 | 38.90 | 70.40 | 7.0 | 0.51 |
| RAC20F2 | 331.2 | 592.2 | 77.60 | 140.9 | 7.0 | 0.51 |
| RAC30F2 | 289.8 | 518.2 | 116.4 | 211.3 | 7.0 | 0.51 |
| NACF3 | 414.0 | 740.2 | - | - | 10.5 | 0.51 |
| RAC10F3 | 372.6 | 666.2 | 38.90 | 70.40 | 10.5 | 0.51 |
| RAC20F3 | 331.2 | 592.2 | 77.60 | 140.9 | 10.5 | 0.51 |
| RAC30F3 | 289.8 | 518.2 | 116.4 | 211.3 | 10.5 | 0.51 |

Cement: 350 kg, FA: 756.5 kg

C. Test Methods

The SP dosage was adjusted according to the manufacturer's guidelines to maintain the slump values within the 3-5 cm target range. For each experiment, three specimens per mixture were tested. Due to the large number of mixtures prepared and laboratory space limitations, the sample size could not be more significant. The specimens were cured in water for 28 days. The properties of the concrete were measured as:

- Compressive strength was tested on $10 \times 10 \times 10$ cm³ cubic specimens following the NF EN 12390-3 standard.
- Flexural strength was determined using a four-point flexural test performed on $40 \times 10 \times 10$ cm³ prismatic specimens under the NF EN 12390-5 standard
- Thermal conductivity was tested on $10 \times 10 \times 10$ cm³ cubic specimens using a CT-meter, following the NF EN 993-15 standard.

III. RESULTS AND DISCUSSIONS

A. Compressive Strength

Figure 4 illustrates the variation in compressive strength of concrete as a function of the RA substitution ratio. It shows that the compressive strength of RAC typically decreases as the RA replacement ratio increases. Specifically, the compressive strength of RAC30, RAC50, and RAC100 decreased by 14.2%, 20.9%, and 35.5%, respectively, compared to the compressive strength of NAC. These results align with those of previous

studies [3, 6–8, 26], which attribute this decrease in strength to the weaker Interfacial Transition Zones (ITZ) in RAC. Additionally, the presence of adhered mortar on RA promotes the formation of numerous micropores and cracks, which may affect the mechanical performance of RAC. However, MTSMM significantly improved the compressive strength, particularly in mixes containing less than 50% RA. These results suggest that MTSMM can mitigate some of the strength reduction associated with RA incorporation, making RAC a viable option for sustainable construction applications.

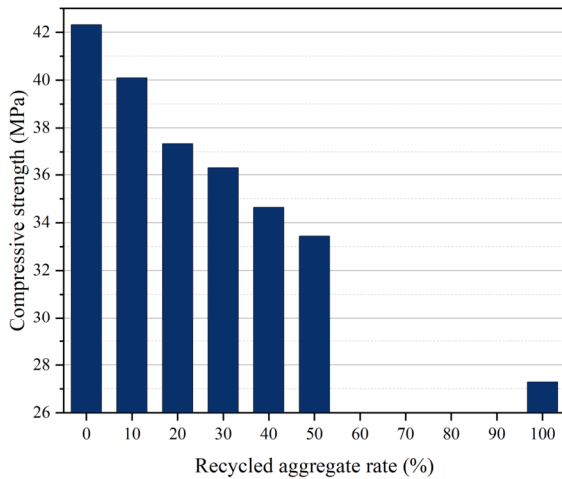


Fig. 4. Effect of RA substitution on the compressive strength of concrete.

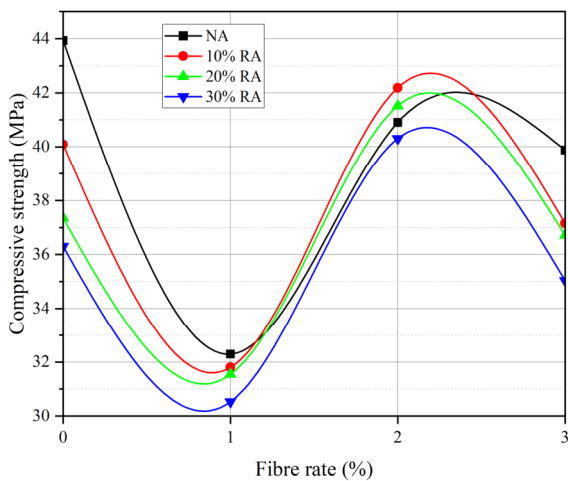


Fig. 5. Effect of RA substitution and DPF additions on the compressive strength of concrete.

For DPFrac, the variation in compressive strength with the RA substitution and DPF addition is presented in Figure 5. The results indicate that adding 1% DPF decreases NAC and RAC compressive strength by up to 26.49% compared to similar fiberless concrete. This trend aligns with the findings of [22], where adding 0.5% rattan and bamboo fibers decreased the compressive strength by 25.03% compared to the reference concrete. This reduction may result from the low ratio of the

added fibers, making it challenging to achieve uniform mixing in the concrete batch. The former can lead to uneven fiber distribution (segregation) in the concrete specimens, ultimately affecting their mechanical performance. However, the RAC mixes prepared with 2% DPF content exhibit higher compressive strength, and achieving that of NAC. Compared to similar fiberless concrete, the compressive strength increases by 5.23%, 11.16%, and 11.05% for RAC10F2, RAC20F2, and RAC30F2, respectively. This trend aligns with the findings of [20], where it was reported that adding 2% DPF to the mixture increased compressive strength by 10.38%. This improvement can be attributed to better fiber dispersion and enhanced material consistency. Concrete can be compacted adequately at this fiber content, and the fibers will be uniformly distributed, preventing segregation and improving material consistency. However, NACF2 exhibits a 6.8% reduction in compressive strength compared to NAC. This suggests that while incorporating 2% DPF may slightly decrease NAC's compressive strength due to microstructural modifications, its positive effects on fracture resistance and durability should also be considered. At 3% DPF content, fiber agglomeration may cause a slight reduction in efficiency, creating voids and reducing the concrete mix's overall homogeneity.

These results highlight the potential of the DPF to compensate for strength losses in RAC. The addition of 2% DPF allows for a significant recovery of strength, suggesting that DPFrac can be a viable structural alternative.

B. Flexural Strength

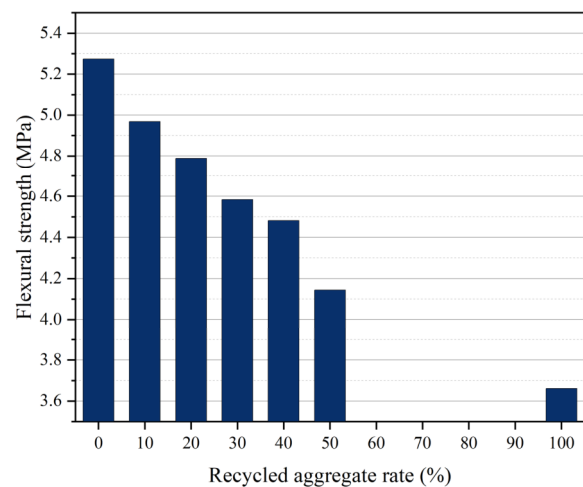


Fig. 6. Effect of RA substitution on the flexural strength of concrete.

The results of the flexural tests on NAC and RAC are displayed in Figure 6. Flexural strength decreases as the RA content increases. The flexural strength of RAC is reduced by 13.1%, 21.42%, and 30.58% with 30%, 50%, and 100% RA replacement, respectively. These findings align with those of previous research [6, 26], where flexural strength reductions ranging from 30% to 50% at 100% RA replacement ratio were reported. The extent of this reduction depends significantly on the quality and treatment of the RA. RA exhibits higher porosity and lower intrinsic strength than NA, which weakens

the bond between the aggregate and the cementitious matrix, leading to an overall reduction in RAC strength.

In Figure 7, which illustrates the variation in flexural strength as a function of RA substitution and DPF addition, it can be observed that adding 2% of DPF enhances flexural strength by 4.27%, 5.89%, and 7.03% for RAC10F2, RAC20F2, and RAC30F2, respectively, compared to companion unreinforced RAC.

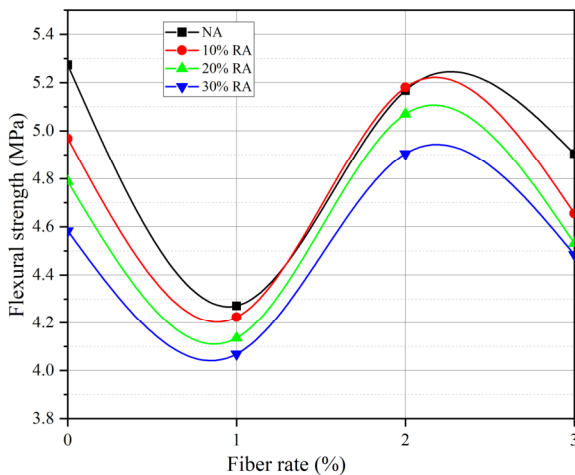


Fig. 7. Effect of RA substitution and DPF additions on the flexural strength of concrete.

This improvement in flexural strength can be attributed to the high tensile strength of DPF, which enhances the material’s ability to resist bending forces and the bond between the concrete and fibers facilitated by the alveolar structures on the fiber surfaces [19]. However, the fibers were torn after testing, which is expected, as the fibers bond well with the concrete matrix. These findings are consistent with those of previous studies [17, 19, 21], which emphasize the importance of optimizing DPF content to maximize concrete performance. Furthermore, authors in [23] reported that adding 3 kg/m³ of DPF increased the flexural strength of RAC by 46.7% compared to unreinforced RAC; these findings confirm that fiber reinforcement effectively mitigates strength losses due to RA substitution, allowing well-designed DPF-RAC mixtures to maintain flexural performance even at a 30% RA replacement level.

C. Thermal Conductivity

Figure 8 depicts the impact of RA substitution on thermal conductivity, showing a progressive decrease as the RA replacement ratio increases. The thermal conductivity of RAC30, RAC50, and RAC100 was reduced by 12.9%, 19.47%, and 31.11% compared to NAC. These observations align with those in [10, 27], where similar reductions were reported, with decreases ranging from 10–20% for 30–50% RA replacements and up to 30% for complete replacements. This reduction is attributed to the increased porosity, which disrupts heat transfer pathways and creates insulating spaces, improving thermal performance. Figure 9 shows the evolution of thermal conductivity as a function of RA and DPF content. Substituting

aggregates and adding DPF has been observed to improve thermal conductivity. Regarding the mixes exhibiting optimal mechanical performance, the thermal conductivity of RAC10F2, RAC20F2, and RAC30F2 was reduced by 11.6%, 12.42%, and 18.27%, respectively, compared to NAC.

These findings indicate that concrete with RA offers enhanced thermal efficiency, rendering it ideal for applications requiring improved insulation, such as energy-efficient buildings and infrastructure with thermal requirements. Overall, Figure 8 highlights RA’s potential as a sustainable construction material, improving thermal performance, reducing energy consumption, and supporting eco-friendly construction practices.

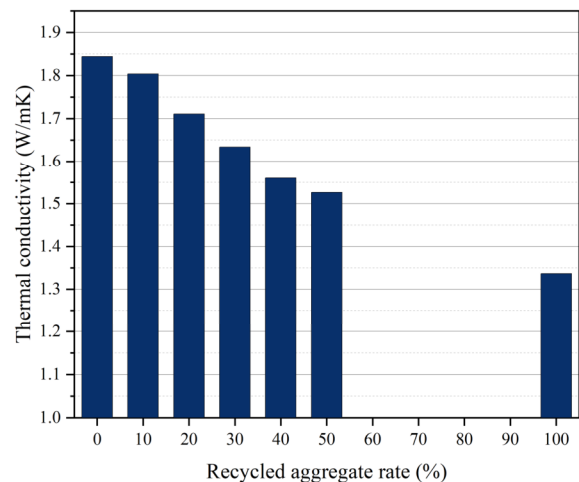


Fig. 8. Effect of RA substitution on the thermal conductivity of concrete.

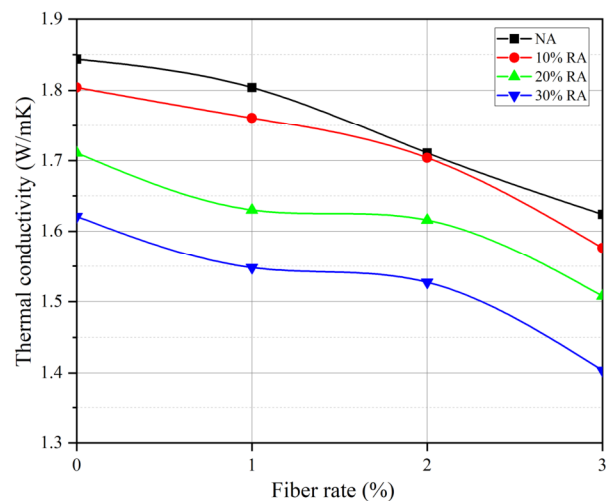


Fig. 9. Effect of RA substitution and DPF additions on the thermal conductivity of concrete.

This reduction is attributed to the increased porosity of the concrete due to the RA addition and the lower thermal conductivity of DPF compared to that of the concrete. This trend aligns with previous findings [17, 21, 28], according to

which DPF was shown to enhance concrete thermal insulation due to its lightweight and porous structure while maintaining acceptable mechanical performance. Furthermore, DPF integration offers a sustainable solution by utilizing agricultural waste and reducing the environmental impact of construction materials [17]. The combination of DPF and RA enhances concrete thermal insulation properties, making it a promising material for energy-efficient buildings, where thermal performance is essential [16, 28].

IV. CONCLUSION

This study examines the mechanical and thermal properties of Date Palm Fiber-Reinforced Recycled Aggregate Concrete (DPFRAC) as a sustainable alternative to conventional concrete. The present research evaluates how Recycled Aggregates (RA) and DPF influence compressive strength, flexural strength, and thermal conductivity using a Modified Two-Stage Mixing Method (MTSMM).

MTSMM significantly improves material cohesion, fiber dispersion, and aggregate bonding, particularly in mixes containing less than 50% RA. As the RA content increases, the mechanical performance of Recycled Aggregate Concrete (RAC) declines. At 100% RA replacement, compressive and flexural strength decrease by 35.5% and 30.58%, respectively. However, incorporating 2% Date Palm Fibers (DPF) reverses this trend and enhances these properties. At 30% RA replacement, DPFRAC gains 7.03% compressive strength and 11.05% flexural strength compared to unreinforced RAC, bringing its performance closer to that of Natural Aggregate Concrete (NAC). These results align with those of previous research, which also reports significant strength improvements in fiber-reinforced concrete with 2% fiber content [20]. Beyond the mechanical benefits, DPFRAC improves thermal insulation. Adding 2% DPF further reduces the latter by 18.27% for 30% RA replacement.

In conclusion, this study confirms that although RA substitution reduces mechanical performance, adding 2% DPF effectively counteracts these effects by improving compressive and flexural strength, enabling DPFRAC to achieve performance levels closer to those of NAC. Furthermore, the findings demonstrate that DPFRAC balances sustainability, mechanical performance, and thermal efficiency. With further refinement, this material can be key in eco-friendly and energy-efficient construction.

Although these findings demonstrate DPFRAC's potential as a sustainable construction material, several challenges remain. RA variability and long-term durability require further research. Future work should increase the RA replacement ratio beyond 30% while integrating advanced RA and DPF treatment methods. Evaluating their impact will help optimize the proportions of RA and DPF, further enhancing concrete mechanical properties and durability.

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