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Microstructural Properties of the Interfacial Transition Zone and Strength Development of Concrete Incorporating Recycled Concrete Aggregate

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Abstract**—**This study investigates the potential of using crushed concrete as aggregates to produce green and sustainable concrete. Crushed concrete was sieved to powder fine recycled aggregate (PFRA) less than 80 µm and coarse recycled aggregates (CRA). Physical, mechanical, and microstructural properties for PFRA and CRA were evaluated. The effect of the additional rates of PFRA and CRA on strength development of recycled aggregate concrete (RAC) was investigated. Additionally, the characteristics of interfacial transition zone (ITZ) between cement paste and recycled aggregate were also examined. Results show that concrete mixtures made with 100% of CRA and 40% PFRA exhibited similar performance to that of the control mixture prepared with 100% natural aggregate (NA) and 40% natural pozzolan (NP). Moreover, concrete mixture incorporating recycled aggregate exhibited a slightly higher later compressive strength than that of the concrete with NA. This was confirmed by the very dense microstructure for concrete mixture incorporating recycled concrete aggregates compared to that of conventional concrete mixture.

Keywords**—**Compressive strength, recycled concrete aggregates, microstructure, interfacial transition zone, powder fine recycled aggregate.

I. INTRODUCTION

SEPARING and reusing concrete from construction-demolished waste (CDW) is paving the way towards sustainable construction [1]. The huge increase in CDW volume is the main challenge facing construction industry [2]. Significant efforts are being made to find ways to reuse these huge amounts of CDW.

The use of recycled concrete as aggregates in new concrete mixtures helps conserving natural resources, decreasing production energy and reducing the amount of waste deposited in landfills [3], [4], which maximizes the economic benefits of CDW [5]. RAC can be incorporated in producing new concrete mixtures (i.e. recycled concrete aggregate concrete (RCAC)) [6], [7].

Concrete made with RA has different characteristics from those of conventional concrete [8], [9]. Depending on the properties of the RA, RCAC strength grade can vary from normal and up to high strength concrete [10]. The properties of RA vary widely due to its different sources and many possible compositions of the original concrete [9]. Moreover, previous research showed that the addition of CRA to concrete does not have an adverse effect on its performance [11]. Conversely, the addition of PFRA as a replacement for cement was found to increase concrete compressive strength significantly [12]. Moreover, the surfaces of RA are wrapped by old cement paste. Hence, the ITZ of RCAC is more complicated than that in NA concrete [13]. Characteristics of the ITZ will depend mainly on the properties of the RCAC such as flowability and strength [12]-[14]. However, information on concrete using PFRA and CRA is still insufficient. Detailed information about characteristics of concrete using RA is needed before its wider implementation in today’s construction.

The present study aims to examine the influence of mechanical and morphology of PFRA and CRA on strength and microstructure development of RCAC.

II. MATERIALS AND TESTING PROCEDURE

A. Materials

Ordinary Portland cement CEM II 42.5 B with a specific gravity of 3.16 kg/m^3 and specific surface area of 3519 cm^2/g according to European Standard EN 197 [15] was used in all mixtures. NP extracted from Bouhamidi deposit in the Beni-Saf region (North- West of Algeria) was used in this study as a mineral admixture. After drying at 105 °C to eliminate free water, CRAs were produced after crushing of waste concrete from the Laboratory of West Algeria Public Works with an average compressive strength of 40 MPa [12]. For PFRA, waste concrete samples were crushed to less than 80 µm, resulting in a specific surface area of 300 m^2/kg. This very fine recycled aggregate powder was essentially composed of silica and alumina (more than 60%). The particle size distributions for RCP and cement are shown in Fig. 1. Table I presents the properties of binders. Both natural and recycled gravels with two size ranging 0.12-0.20 in. (3-5 mm) and 0.39-0.59 in. (5-15 mm) were used as coarse aggregates. Table II lists the

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physical and mechanical properties of used materials.

TABLE I
PROPERTIES OF BINDERS

Property	Addition types		
	NP	PFRA	Cement
Size (µm, Nm)	>80 µm	80 µm- 36.5 Nm	-
Sand Equivalent (kg.m^{-3})	80	76	-
Absorption (%)	1.3	1.35	
Specific Surface (m^2 kg^{-1})	300	4733	3519
Cleanliness (%)	1.3	1.3	-

µm= micrometer, Nm =nanometer, kg.m^{-3}=kilogram per cubic meter, m^2 kg^{-1} = square meter per kilogram. %= percentage

TABLE II
SIZE, PHYSICAL AND MECHANICAL PROPERTIES OF AGGREGATES

Property		Aggregates types				
		NA		RA		Sand
Size(mm)		3-5	5-15	3-5	5-15	0.4
Density(kg.m^{-3})	Apparent	1.355	1.423	1.174	2.544	-
	Bulk	2.586	2.586	2.544	2.543	0.4
Absorption (%)		1.3	1.35	2.5	2.54	0.4
Los Angeles (%)		27	36.95	-	29	-
Cleanliness (%)		1.3	1.3		1.3	-

mm= mile meter. %= percentage, kg.m^{-3} = kilogram per cubic meter

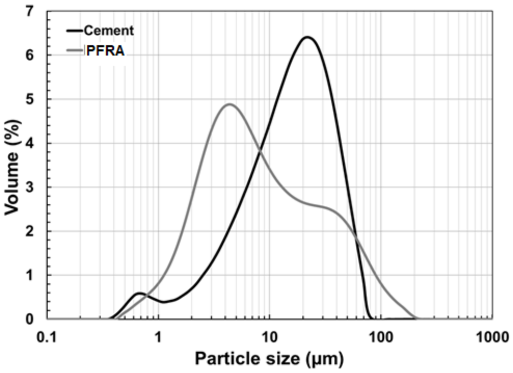

Fig. 1 Laser particle size distribution for the used cement and FRCA

B. Specimen Preparation

Four mixtures concrete were mixed and prepared according ASTM C 192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory) [16]. The first mixture (NC) was prepared with 100% NA and 40% NP, the second mixture 100 % (NA-PFRA) with 100% NA and 40% PFRA, the third mixture (100CRA-NP) with 100% CRA and 40% NP and the last one (100CRA-PFRA) with 100% CRA and 40% PFRA, the third mixture (100CRA-NP) with 100% CRA and 40% NP and the last one (100CRA-PFRA) with 100% CRA and 40% PFRA. In all mixtures, the total free water-cement ratio (w/c) was kept constant at 0.5. A polycarboxylate-based high range water reducing admixture (HRWRA) conforming to ASTM C494 [17] standard type F was also added to the mixtures to maintain their slump in the range of 2.55-2.95 in. (65-75 mm). Air-entraining admixture (AEA) was added in the range of 35–65 ml/100 kg binder targeting a fresh air content of 5±1%. Mixtures compositions are given in Table III.

Cubic specimens with dimension of 2.75 in (7cm) were used to evaluate compressive strength tests according to NF P 18- 400 [18] at ages 3, 28, 90, 180, 360, and 720 days using a 3000 kN capacity compression testing machine. All specimens were demolded after 24 h and moist cured at a temperature (20±2 °C) and 95% relative humidity (RH) until testing age.

TABLE III
MIXTURE PROPORTIONS (KG/M³) OF RAC CONCRETE

Mix designation		Control NC	100NA-PFRC	100CRA-NP	100CRA-PFRA
Cement		350	350	350	350
NA	3-5(mm)	204	204	-	-
	5-15(mm)	587	587	-	-
CRA	3-5(mm)	-	-	204	204
	5-15(mm)	-	-	587	587
Sand		887	887	887	887
NP		140	-	140	-
PFRA		-	140	-	140
Water/Cement		0.5	0.5	0.5	0.5
Slump(mm)		72	74	70	78

mm= mile meter

III. TEST RESULTS AND DISCUSSIONS

A. Properties of Recycled Concrete Aggregate

Fig. 2 presents the particle size distribution for CRA with different sizes with respect to the standard grain distribution range acceptable by ASTM C33-13 [19]. The particle size distribution curves of all samples are within the acceptable ranges. Figs. 3 and 4 illustrate the appearance of CRA and NA. Particles in CRA are clearly rougher in shape and more angular than those in NA as well as more grayish in color. This difference in shape can be attributed to the repeated crushing. The materials were produced from concrete waste and thus had cement paste adhered to the larger fragments, as shown in Figs. 4 and 5. Table II presents the size, physical, and mechanical properties of aggregates used. It shows that 0.39-0.59 in. (5-15 mm) aggregates have a lower density (bulk) and higher water absorption than does NA. Furthermore, the Los Angeles abrasion value for CRA is 36.95%. This value is higher than those for NA and arises because of the adhering cement paste and the higher bond between attached mortar and NA [20].

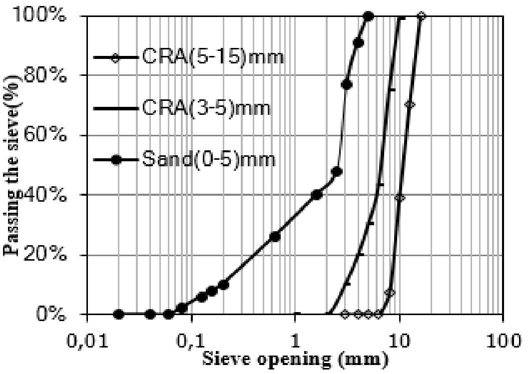

Fig. 2 The gradation of recycled aggregates used and sand

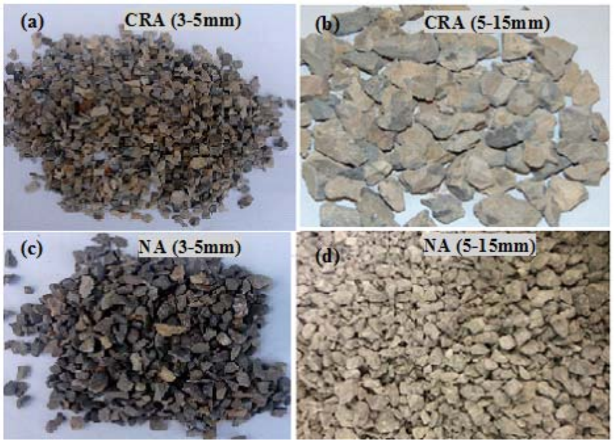

Fig. 3 (a), (b): CRA and (c), (d): Coarse natural aggregates

B. Compressive Strength

Variations in compressive strength with time for all tested mixtures are shown in Fig. 6. Compressive strength for all mixtures increased after 28 days. At 28 days, results showed that the use of 40% PFRA produces no major significant changes with respect to the NC. Moreover, with a value of 32 MPa taken as the minimum acceptable strength for concrete exposed to sulphate environment [21], all concretes of 28 days and older (60, 90, 180 days) fulfilled this condition. Regardless type of aggregate, mixtures incorporating PFRA exhibited the highest compressive strength especially at early ages. For instance, at age 7 days, compressive strengths for mixtures 100NA-PFRA and 100CRA-PFRA were higher than those of mixtures NC and 100NA-NP with about 12% and 11% respectively. This is likely due to acceleration and densification effects of PFRA [12]. RCP contains calcium silicate hydrates (C-S-H) and calcium hydroxide (CH) shown in Fig. 7. Some authors [22], [23] had indicated that the addition of CH and/or C-S-H will accelerate the hydration reactions as it acts as a nucleus for further C-S-H formation. Moreover, crystalline CH acts as a sink for calcium and silicate ions in the solution, enabling further dissolution of tricalcium silicate (C3S) and renewed C-S-H formation. On the other hand, PFRA is finer than the cement and has smaller particles size (Fig. 1). Hence, added PFRA particles will densify the microstructure through enhancing particle packing and consequently reducing the amount of space needed to be filled by hydration products.

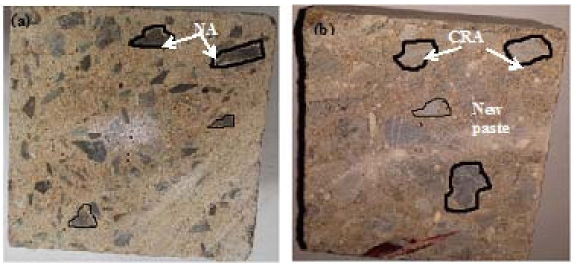

Fig. 4 Sectional Concrete: (a) conventional concrete and (b) CRA and (c), (d): Coarse NAs

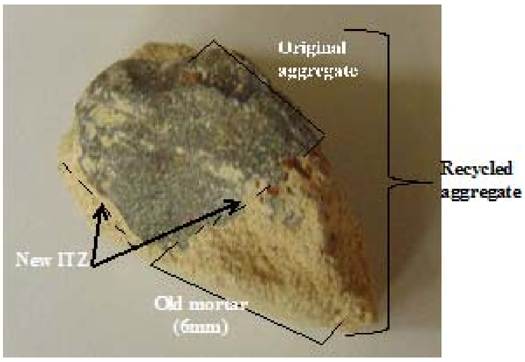

Fig. 5 Sectional view of CRA

When the substitution is 100% CRA, there is a significant increase of compressive strength. At 180 days, it is found that the difference between the compressive strength of the NC and the 100NA-PFRA is higher for stronger concretes. This is attributed to the effect of ITZ between the adhesion mortar and the new mortar. Figs. 8 and 9 (a), (b) compare graphic representations and SEM images of the ITZ of conventional concrete and recycled concrete. It is found that the additional interface between the attached mortar and the new cement paste is responsible for a better bond RA/cement paste compared to NA/cement paste [13].

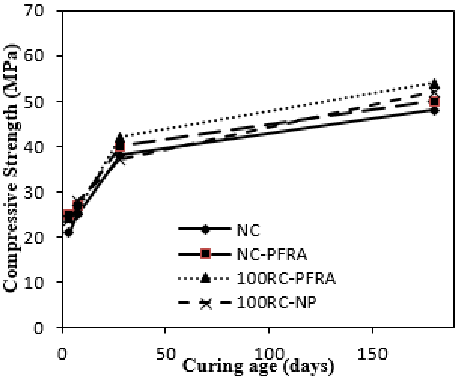

Fig. 6 Compressive strength tests

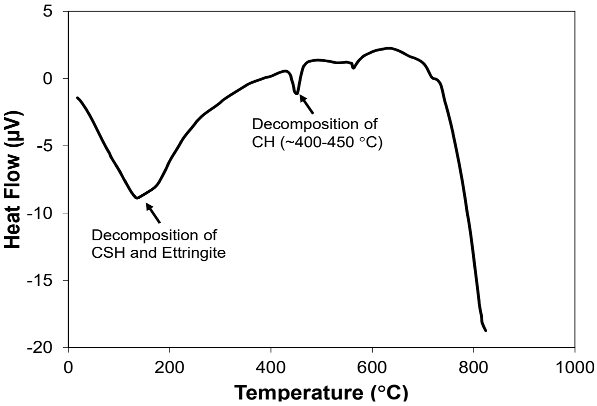

Fig. 7 TGA results for PFRA

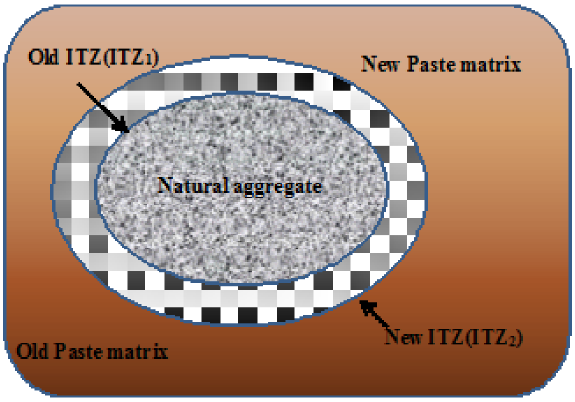

Fig. 8 Schematic diagram of old and new ITZ in RAC

C. Analysis of ITZ

Scanning Electron Microscopy (SEM) examinations were carried out on the fracture and polished surface of the recycled concrete. The SEM analysis had focused on the matrix-coarse aggregate interfacial regions. The interface plays a significant role in development of concrete strength. In RAC, two interfaces exist: the interface between adhered mortar and the original aggregate ITZ1 (old ITZ), and the new ITZ between the new mortar and the recycled aggregate ITZ$_2$ (new ITZ), are shown in Figs. 9 (c), (d) and 10 (a), (b).

Figs. 10 (a), (b) show the recycled concrete – cement interface microstructure. The RCAC had the highest interfacial zone density). The presence of unhydrated cement grain in the matrix indicates the existence of the other hydration product phase which can be attributed to the greater compressive strength of concrete produced with CRA and PFRA [12], [13], shown in Figs. 9 (a) and 10 (b). This translates directly to increased adhesion of cement paste - recycled aggregate to increase in the mechanical strength of ITZ.

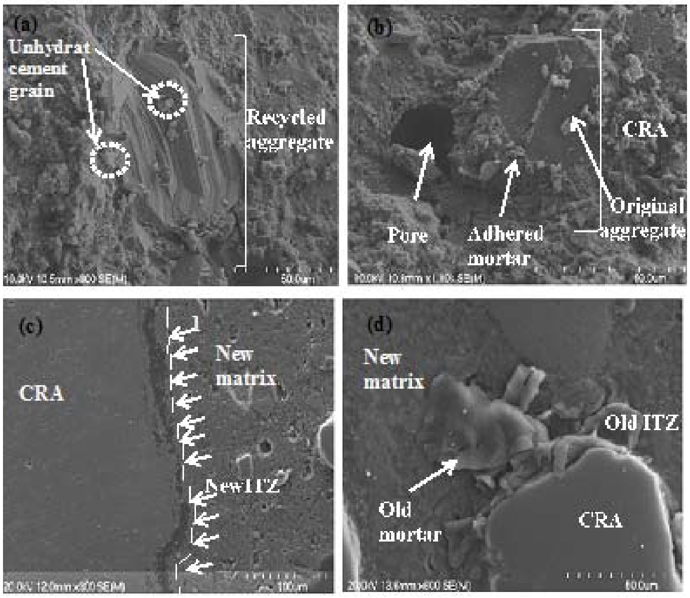

Fig. 9 (a) and (b) SEM images of surface microstructure of the recycled concrete after fracture of the specimen 100CRA-PFRA; (c) and (d) Interface of polished surface of recycled concrete. (1) represents the force of adhesion (new cement matrix: PFRA + cement which penetrated into the aggregate's structure)

Recycles coarse aggregate with moderate initial moisture content absorbed a certain amount of free water and lowered the initial w/c in the ITZ at early hydration. Newly formed hydrates gradually filled the region [24]. These processes effectively improved the interfacial bond between the recycled concrete – cement matrix. Generally, the SEM observation revealed that a dense ITZ was present between the CRA and the cement matrix. According to Etxeberria et al. [25], the new ITZ between the recycled aggregate and the cement paste was effective. However, the higher absorption of CRA used in the mixture significantly decreased the w/c leading to higher bond, cohesion, and coherence between the new cement past and recycled coarse aggregate. On other hand, the recycled coarse aggregate has very rough surface and high porosity, which makes water and cement paste penetrate into the structure of aggregate creating strong mechanical and physical bond between new cement paste and aggregate. The increase of adhesion between two surface and surface tension signified to increase the adhesion between cement paste and recycled coarse aggregate Figs. 9 (c) and (d). It is probably due to the formation of "mechanical hooks" created by the penetration of recycled concrete powder and cement matrix into the pores of aggregate in recycled concrete structure. This result is quite comparable with the research of Zegardło et al. [26].

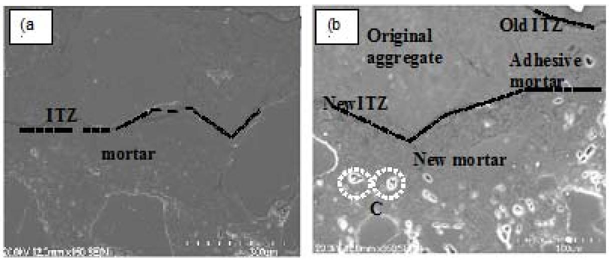

Fig. 10 Comparison of ITZs of (a) Naturel aggregate NA and (b) RAC; (c) Unhydrated cement grain

IV. CONCLUSION

The physical and mechanical results of recycled coarse aggregate proved the good quality of aggregate and replay this criterion (specific density higher than 2160 kg/m^3), water absorption lower than 8% and Los Angeles abrasion loss under 40% (LA40), are obtained for the production of structural concrete. This quality of recycled aggregate can be produced controlling original concrete strength, over 25 N/mm^2. This recycled aggregate can be used in high-strength concrete according to requirements Japan BCSJ (JIS A5021 205) [27].

PFRA added up to 40% improved the strength recycled concrete through acting as a nucleation sites for new hydration products and densifying the microstructure. The difference in strength development between the recycled concretes and conventional concrete strength was due to the differences in both the strength of the coarse aggregates and the microstructural properties of the ITZs.

The microstructure of the interracial transition zone for concrete with recycled aggregate was found to be a governing factor for the strength development of the RAC. It is interesting to note that there is a stronger and denser new transition interfacial zone ITZ2 in RCAC.

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