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Influence of Surface-Treated Coarse Recycled Concrete Aggregate on Compressive Strength of Concrete

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***Abstract*—**This paper reports on the influence of surface-treated coarse recycled concrete aggregate (RCA) on developing the compressive strength of concrete. The coarse RCA was initially treated by separately impregnating it in calcium metasilicate (CM) or wollastonite and nanosilica (NS) prepared at various concentrations. The effects of both treatment materials on concrete properties (e.g., slump, density and compressive strength) were evaluated. Scanning electron microscopy (SEM) analysis was performed to examine the microstructure of the resulting concrete. Results show that the effective use of treated coarse RCA significantly enhances the compressive strength of concrete. This result is supported by the SEM analysis, which indicates the formation of a dense interface between the treated coarse RCA and the cement matrix. Coarse RCA impregnated in CM solution results in better concrete strength than NS, and the optimum concentration of CM solution recommended for treated coarse RCA is 10%.

***Keywords*—**Calcium metasilicate, compressive strength, nanosilica, recycled concrete aggregate.

I. INTRODUCTION

ONE of the most remarkable differences between recycled coarse aggregate (RCA) and natural aggregate is that RCA is composed of natural aggregate with a certain amount of mortar (cement paste) adhering to the aggregate particles.

Adhered mortar content has a significant effect on RCA properties because adhered mortar is porous [1], [2] and has numerous cracks [2], which can cause adverse effects on RCA properties compare to natural aggregate (e.g., high water absorption capacity, lower density, and lower strength). The poor qualities of recycled aggregate, which crucially affect the performance of concrete, have become a challenge, and the issues have limited the widespread commercial use of recycled aggregate in concrete production [3]. Therefore, recycled aggregate is suggested mainly to be used in non-structural or lower-grade concrete applications [4]. However, the necessity and value of using recycled aggregate, which greatly benefits the economy and environment, resulted in the recent immergence of intensive research focusing on determining methods with which to reduce the adverse effects of recycled aggregate in concrete production.

Researchers have employed various treatment methods and technologies to produce recycled aggregate and ensure that its properties qualify as aggregate material for use with concrete. Surface treatment is a beneficial method proposed to overcome the weaknesses of recycled concrete aggregate (RCA) and improve RCA quality prior to mixing. This method involves using suitable admixtures as microfillers to refill pores and cracks as well as improve the physical surface of RCA. Previous studies show that different coating methods and potential material coatings have been used to treat RCA surfaces. One method involves immersing RCA in silica fume diluted in distilled water for several hours [5]. Another RCA impregnation technique involves adding various proportions of silica fume and metakaolin in a colloidal silica solution and keeping the solution pressurised in a vacuum [6]. Alternatively, the RCA is soaked in nanosilica (NS) solution [7] or in a polymer solution while being pressurised in a vacuum [1]. Other methods include coating RCA using types of oil and silane as surface-improving agents [8]. These methods significantly assist in consolidating the adhering mortar layer and filling up pores in the RCA, thereby reducing the porosity and water-absorption characteristics of RCA. Previous studies prove that surface treatment improves the interfacial bonds between the RCA and the novel cement paste in the novel concrete and enhances concrete performance. However, the surface treatment method is highly dependent on selecting suitable materials or admixtures for the treatment. Constant exploration of new materials is necessary to determine the most suitable material to produce optimal results in enhancing RCA quality and minimise their adverse effect on concrete performance. This study contributes to the knowledge of methods to increase RCA quality and encourages the widespread use of this material in concrete production.

The study demonstrated a method of treating coarse RCA by impregnating it in various concentrations of calcium metasilicate (CM) and NS. The study investigates the influence of both impregnation materials on the compressive strength of the resulting concrete product. An experimental investigation was conducted to determine the most suitable and optimal solution concentration for the RCA treatment which contributes to the maximum results on compressive strength properties of the concrete.

II. EXPERIMENTAL

A. Materials

The cement used in this study was ASTM Type I Portland cement with a density of 3.15 g/cm3 and specific surface area of 3960 cm2/g. The chemical compositions of the cement are

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given in Table I. River sand with specific gravity 2.51 and fineness modulus 3.98 used as fine aggregate. In this study, all of the coarse aggregates used had a maximum size of 20 mm and were predominately 5 mm in size. Crushed granite was used as the natural coarse aggregate. The coarse RCA used was generated from crushing waste concrete that mainly consisted of tested concrete cubes. Table II presents the gradation of all aggregate based on a sieve analysis, and Table III compares the physical and mechanical properties of coarse natural aggregate and RCA. The two selected materials used for the surface coating of coarse RCA were CM and colloidal amorphous nanosilica. Berjaya Bintang Timur Sdn Bhd supplied the CM used in this study, which was in white powder form and the particles were in acicular form or needle-like structure (Fig. 1 (a)). Sigma Aldrich supplied the Ludox HS40 nanosilica used. Fig. 1 (b) shows the SEM of the nanosilica. Table I presents the physical properties and chemical compositions of both materials.

TABLE I
PHYSICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF CEMENT, CM, AND NS

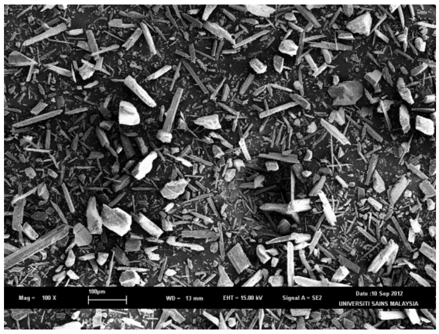
Chemical composition	Mass (%)		
	Cement	CM	NS
SiO_2	16	50.32	98.88
Al_2O_3	3.6	0.77	0.04
Fe_2O_3	2.9	0.33	0.09
CaO	72	44.44	0.06
MgO	1.5	1.31	0.07
K_2O	0.34	0.15	0.04
P_2O_5	0.06	0.08	0.02
MnO	0.03	0.05	0.03
TiO_2	0.17	0.03	0.01
Others	3.41	2.52	0.76
Loss on ignition	2.53	0.46	0.43
Physical properties			
Phase	powder	powder	liquid
Surface area		1.8 m^2/g	~220 m^2/g
Density	3.15 g/cm^3	2.87 g/cm^3	1.3 g/mL at 25 °C
Colour	grey	white	transparent

TABLE II
SIEVE ANALYSIS OF THE FINE AND COARSE AGGREGATE

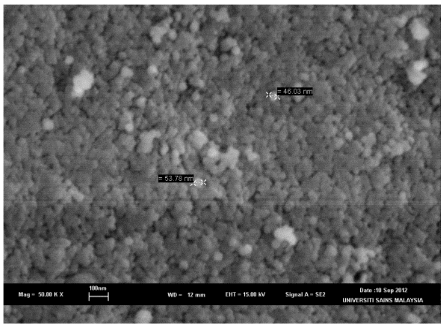
Aggregate	Aggregate passing (%) according to sieve size (mm)								
	0.15	0.3	0.6	1.18	2.36	5	10	14	20
Fine	0.9	8.8	22.7	45.3	77.4	100	100	100	100
Coarse Natural	0.0	0.0	0.0	0.0	0.2	0.2	31	59.2	100
Coarse RCA	0.0	0.0	0.0	0.0	0.4	0.8	30	60.4	100

TABLE III
PHYSICAL AND MECHANICAL PROPERTIES OF COARSE NATURAL AGGREGATE AND RCA

Properties of Aggregate	Natural Granite	RCA
% Mortar Content (Average)		20 - 45
Particle Density - Oven Dry (Mg/m^3)	2.6	2.3
Water absorption (%)	0.7	5.01
Agg. Crushing Value (%)	24.32	29.15
Agg. Impact Value (%)	13.98	21.78
LA Abrasion Value (%)	34.76	39.12



(a)



(b)

Fig. 1 SEM of (a) CM (b) nanosilica

B. Surface Treatment of RCA

Coarse RCA treatments (impregnation) were conducted separately according to their respective surface coating materials, which were prepared at various concentrations. The treatment procedures were as follows: (i) The coarse RCA was completely dried in an oven for 24 h at 105 °C and then cooled at room temperature. (ii) The CM and NS solutions were prepared at different concentrations by separately dissolving both materials into distilled water. The CM was added at 5%, 10%, 15% and 20%, and the NS was added at 0.25%, 0.50%, 0.75% and 1% into distilled water to create different concentrations. All added materials were calculated based on the weight of the distilled water. The mixture was stirred for several minutes to ensure the proper dispersion of the CM and NS particles. (iii) The dried RCA was then immediately added into the solution. The quantity of the RCA added was based on the weighted water-to-coarse RCA ratio of 1:1.7. (iv) The RCA particles were kept soaked in the solution for 24 h. (v) After immersion, the aggregates were drained for 10 min. (vi) Finally, the RCA was dried in an oven at 105 °C for 24 h. The RCA was cooled to room temperature before being used in the concrete mixture. Fig. 2 illustrates the SEM image of the coarse RCA after impregnation with CM and NS.

C. Mix Design

The mix concrete design followed the DOE method [9], which was prepared for all concrete mixtures to achieve the targeted compressive strength of 50 MPa on the 28th day. Table IV shows that the mixture proportions were kept constant for all mixtures. The dosage compositions of coarse aggregates in all RCA mixes were designed by replacing the natural coarse aggregate with untreated and treated RCA at 60% weight of the total coarse aggregate content. A total of nine series of mixtures were prepared for this study. One batch of mixtures (CON) was prepared with untreated RCA, which served as the control sample for comparison purposes. The rest of the coarse RCA was treated or coated with CM and NS at varying concentrations.

TABLE IV
MIX PROPORTION

Constituents	Proportion (kg/m^3)
Water	210
Cement	512
Sand	722
Coarse Aggregate	
Granite	382
RCA	574

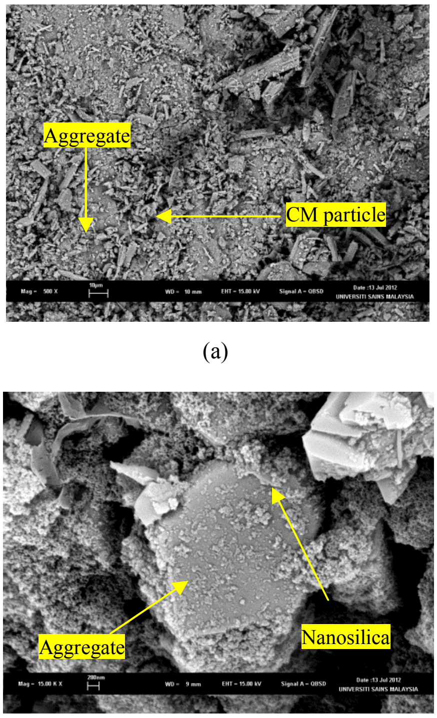


Fig. 2 Surface microstructures of RCA after treated with (a) CM (b) nanosilica

D. Mixing

All concrete mixes in the study were prepared following the procedure prescribed in BS1881-125 [10]. Once concrete mixing was completed, the fresh concrete mixture was placed in a standard testing mould consisting of a 100 mm cube. The specimens were left to cure in the mould for 24 h prior to demoulding. After demoulding, all of the specimens were placed in a PVC tank and initially cured by pounding with water at 25±2°C until the time of testing.

E. Testing

Three testing programs were designed to determine the effect of treated RCA on concrete, which determine concrete workability, density, and compressive strength. Slump tests of fresh concretes were conducted to determine concrete workability immediately after mixing. The slump test procedure was conducted in accordance with BS EN 12390-2 [11]. The bulk density of hardened concrete was tested based on BS EN 12390-7 [12]. The 100-mm concrete cube specimens were moulded and cured. The compressive strength test was conducted in compliance with BS EN 12390-3 [13] on 100 mm concrete cubes under uniaxial compression using an ELE International compression testing machine. Beside, the scanning electron microscopy (SEM) analysis is performed to visualise the micro-pores structures of related concrete mixes produced. All results on concrete properties, whether fresh or hardened, containing treated RCA were analysed and compared with concrete using untreated RCA, which act as control specimens.

III. RESULTS AND DISCUSSIONS

A. Slump Test

Fig. 3 shows the slump test results on the workability of each batch of concrete mix. The results show that the slump of concrete prepared with treated coarse RCA was lower than that of the control sample, and the slump rate decreased as the solution concentration increased during the treatment process. This finding indicates that the concrete mix in CM generally produced a lower slump value than in NS. Among the mix specimens, the lowest slump value of only 35 mm was achieved with CM20. This behaviour was due to the high concentration of CM prior to treatment, which increased the CM coating on the coarse RCA particles. An enhanced specific surface area for the CM particles resulted, which covered the RCA surface. Consequently, extra free water was absorbed during the mixing process.

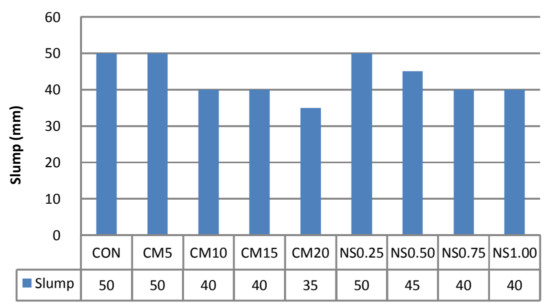


Fig. 3 Slump test results for all specimens

B. Bulk Density of Concrete

Fig. 4 illustrates the bulk density of hardened concrete of all specimens for 28 days. The figure shows that the control specimens have the lowest density among all concrete specimens because of the low particle density of coarse RCA. However, the results indicate that the densities of all concrete specimens that consisted of treated coarse aggregates were higher than those of the control specimens. This finding is due to the reaction of CM and NS to the new cement paste, which increases the hydration of the cement product and makes the concrete specimen with treated RCA denser than the untreated RCA. The results show that the concrete mix in CM had greater densities than that in NS. CM15 exhibited the highest density of 2464 kg/m^3, closely followed by CM10 with 2459 kg/m^3.

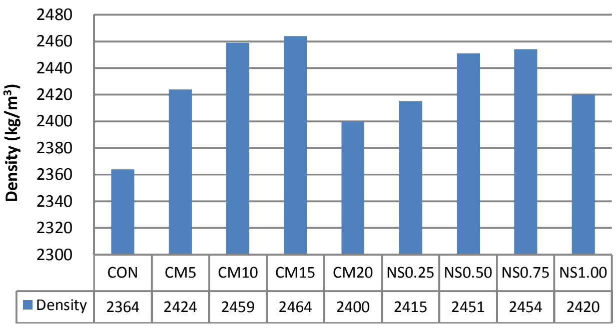


Fig. 4 Bulk density of all specimens at 28 days

C. Compressive Strength

Fig. 5 reports the compressive strength results for all tested specimens. All concrete mixes generally exhibited a similar profile for strength development, in which compressive strength increases with curing age. The figure shows that replacing the coarse natural aggregate with 60% untreated RCA significantly affected the compressive strength of the RCA. The compressive strength of the control concrete specimen prepared with untreated RCA at 28 days was 47 MPa, which was below the mix strength target of 50 MPa at 28 days. By contrast, the concrete specimen prepared with treated RCA performed better than the specimen prepared with untreated RCA. On the 28th day of concrete curing, most of the concrete mixes with treated coarse RCA exhibited higher strengths than the corresponding control specimens and achieved the strength design target. Compared with the control concrete specimen on the 28th day, CM10 exhibited the highest compressive strength at 56.18 MPa, which was equivalent to a 20% increment in strength. Therefore, impregnating coarse RCA at 10% concentration of CM produces optimum results for the compressive strength of concrete. The effect of including concrete with coarse RCA in a CM15 mix produced a similar compressive strength as the CM10 mix. However, increasing the CM concentration beyond 15% adversely affected the compressive strength. The compressive strength of the CM20 mix at 28 days was achieved at 44 MPa, which was 7% lower than the control specimens. This behaviour was due to the excessive amount of CM, which resulted in an incompatibility between the composite materials particularly at the interface bond between the RCA and cement matrix.

In the case of treated coarse RCA with NS, the compressive strength was unaffected by including treated RCA at low concentrations. The compressive strength of NS0.25 at 28 days was comparable with the control concrete specimen. By contrast, the results indicated that NS concentrations beyond 0.25% for treated RCA significantly increased the compressive strength. Among the specimens, NS0.50 had the highest compressive strength at 28 days. In 28 days, the compressive strength obtained for NS0.50 was 54 MPa, which was 15% higher than that for the control specimen. This result suggests that 0.5% is the optimal concentration for NS.

According to the findings from the compressive strength analysis, using both types of treated coarse RCA has significant results in enhancing the compressive strength of concrete. Factors that contribute to enhancing compressive strength are: (i) impregnating RCA with CM or NS to modify the RCA surface. The fine characteristics of the CM and NS particles refill the pores and cracks on the RCA surface and reduces the porosity of the RCA; (ii) decreasing the number of pores and absorption characteristics of the RCA after treatment, which minimises inner bleeding from the new mortar to the RCA and causes cracks at the interfacial transition zone (ITZ) between the new cement paste and the aggregate [14]; (iii) dissolving the CM and NS particles that adhere to the RCA surface during concrete mixing, which reacts with the cement paste during concrete hardening. This reaction also increases the hydration product and forms a strong and dense cement gel, which fills up the loose layers and strengthens the interface bond between the aggregate and cement matrix [6], [7], [15], [16].

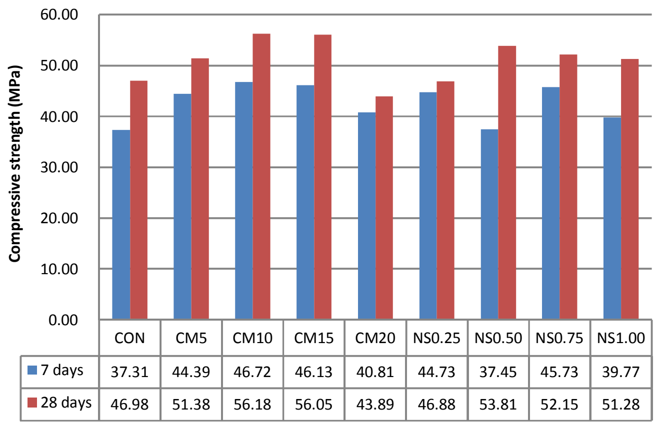


Fig. 5 Compressive strength of all specimens at 7 and 28 days

The SEM examinations conducted to examine the fracture surfaces of the concrete specimens, which were prepared with treated (based on optimal results) and untreated RCA, also support the results of this study. The SEM examinations focused on the ITZ between the new cement paste and the coarse aggregate. Generally, the SEM observations revealed that a porous and loose ITZ existed between the untreated RCA and the new cement paste (Fig. 6 (a)). By contrast, Figs. 6 (b) and (c) show that a dense ITZ existed between the treated RCA and the new cement paste. Both figures illustrate that using treated RCA coated in either CM or NS led to an accelerated and enhanced formation of large quantities of hydration products. This phenomenon improves the microstructure of the ITZ and therefore increases the compressive strength of concrete.

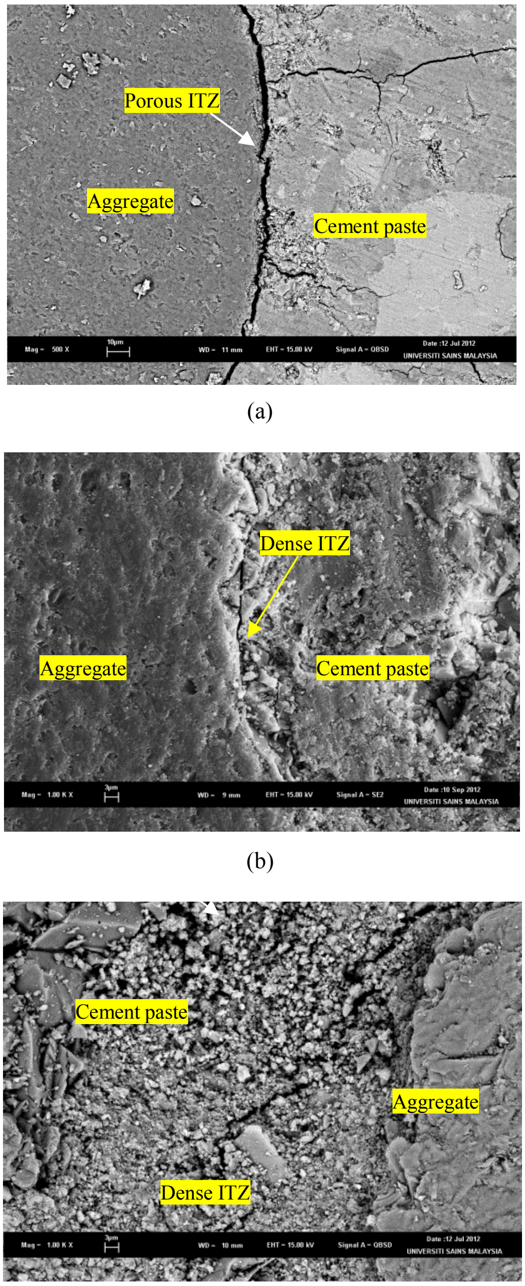


Fig. 6 SEM images of the ITZ between new cement paste and the coarse aggregate (a) untreated RCA (b) treated RCA (CM10) and (c) treated RCA (NS0.50)

IV. Conclusion

The following conclusions were drawn from the investigation:

The concrete slump with treated coarse RCA decreased as the concentration of the material solution for RCA treatment increased. The effect on workability or concrete slump was remarkably affected, particularly for the concrete mix in CM.

The densities of all concrete specimens with treated coarse RCA were higher than the density of the concrete with untreated RCA.

The compressive strength of concrete was significantly enhanced with treated RCA. Treated RCA with CM exhibited better compressive strength than that treated with NS.

Among the specimens, CM10 achieved the highest compressive strength at 28 days, which suggests that 10% is the optimum concentration of CM for treated coarse RCA.

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