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Effect of Different Moisture States of Surface-Treated Recycled Concrete Aggregate on Properties of Fresh and Hardened Concrete

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***Abstract*—**This study examined the properties of fresh and hardened concretes as influenced by the moisture state of the coarse recycled concrete aggregates (RCA) after surface treatment. Surface treatment was performed by immersing the coarse RCA in a calcium metasilicate (CM) solution. The treated coarse RCA was maintained in three controlled moisture states, namely, air-dried, oven-dried, and saturated surface-dried (SSD), prior to its use in a concrete mix. The physical properties of coarse RCA were evaluated after surface treatment during the first phase of the experiment to determine the density and the water absorption characteristics of the RCA. The second phase involved the evaluation of the slump, slump loss, density, and compressive strength of the concretes that were prepared with different proportions of natural and treated coarse RCA. Controlling the moisture state of the coarse RCA after surface treatment was found to significantly influence the properties of the fresh and hardened concretes.

***Keywords*—**Moisture state, recycled concrete aggregate, surface treatment.

I. INTRODUCTION

THE use of RCA can reduce the extensive dependency on natural aggregate resources in concrete production, which are predominantly used for civil construction. However, technical problems are encountered when using the RCA obtained from crushing concrete waste. The physical properties of RCA are generally different from that of natural aggregates. RCA is composed of natural aggregates and a specific amount of adhered mortar that surrounds the original aggregate particles. RCA has highly variable properties because this aggregate is obtained from various sources with properties that are dependent on the mix design composition of the original concrete. The presence of adhered mortar will produce RCA that is relatively more porous, with higher water absorption characteristics as compared with natural aggregates [1], [2]. When RCA is incorporated in new concrete, the higher water absorption capacity of RCA causes difficulties in controlling the effective water/cement (w/c) ratio, which decreases the workability of fresh concrete [3] and consequently influences the strength [4], [5] and durability [6], [7] of the hardened concrete. Therefore, the unfavorable properties of RCAs have limited their widespread acceptability, especially in structural concrete applications.

Surface treatment has been proposed to overcome the weaknesses of RCA and to improve RCA quality prior to mixing. This method involves the use of suitable admixtures as microfillers to refill the pores and cracks and to improve the physical surface of RCA. As demonstrated by previous studies, different coating methods and potential material coatings have been used to treat the RCA surfaces. One method involves several hours of immersing the aggregates in pozzolanic micropowder that was diluted in distilled water. The micropowder, such as silica fume [8], and metakaolin, is usually kept pressurized in a vacuum [9]. Alternatively, the RCA is soaked in a nanosilica solution [10] or is soaked in a polymer solution while being pressurized in a vacuum [2]. Other methods include coating RCA with types of oil and silane as surface-improving agents [11]. These methods significantly assist in the consolidation of the adhering mortar layer and can fill up pores in RCA. Consequently, the porosity and water absorption characteristics of RCA are reduced. These previous studies have proven that surface treatment can improve the interfacial bonds between RCA and the new cement paste in the new concrete, thereby improving the concrete performance.

The effectiveness of this surface treatment method for RCA is dependent on the selection of suitable materials or admixtures that are used for treatment. However, the possible process involved should be taken into consideration. The selection of the techniques to make the treated material adhere to the coating and to refill the aggregate particle surfaces during treatment needs to be considered. As demonstrated by the abovementioned previous studies [2], [8]-[10], the most common surface treatment method involves immersing the RCA in a liquid solution. The fluidity of the treated materials in the aqueous media will allow for more practical and facile dispersion and absorption. Thus, filling in pores at the aggregate surface will be more effective, especially when these are pressurized. However, the immersion of RCA in an aqueous solution during surface treatment influences its moisture content after the treatment. Given the high water absorption capacity of recycled aggregates, measuring the moisture content of RCA is important to develop an effective w/c ratio during concrete production [3]. The different moisture states of the recycled aggregates significantly affect the workability and strength properties of fresh and hardened concrete [12]. Poon et al. [3] and Pelufo et al. [12]

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discouraged the use of over-wetted RCA, which could lead to bleeding problems that may have detrimental effects on the strength of hardened concrete. The influence of the RCA moisture states on the properties of fresh and hardened concretes prepared with recycled aggregates have been previously studied [3], [12], [13]. However, the effect of the controlled moisture states of RCA after surface treatment on the fresh and hardened concrete mixes has not been fully investigated. The effects of surface treatment can modify the physical properties of treated RCA, which slightly differ from those of untreated RCA. The presence of treated material on the RCA surface may likewise influence the changing moisture states of RCA after treatment. Therefore, controlling the moisture content of RCA after surface treatment is necessary.

This study evaluated the appropriate moisture content of coarse RCA after surface treatment that was necessary to influence and improve the properties and performance of fresh and hardened concrete. This study focused on surface treatment using a mineral admixture. Calcium metasilicate (CM) was used in this study as the coating material on the coarse RCA surface. Experimental tests were conducted to understand the effect of surface treatment on the physical properties of coarse RCA. These tests determined the fresh concrete workability and compressive strength of hardened concrete at various ages, which were prepared with either the natural aggregate or the treated RCA at different initial moisture states.

II. EXPERIMENTAL

A. Materials

The cement used in the concrete mixtures in this study was ordinary Portland Cement Type I with a specific surface area of 1.0432 m^2/g and a specific gravity of 3.02. CM was used as the mineral admixture to coat the surface of the coarse RCA. The typical chemical composition of ordinary Portland cement and CM are listed in Table I. The natural coarse aggregates in this study were crushed granite, which were sourced from a local quarry, with maximum sizes of 20mm. The coarse RCA used for this research was produced by crushing waste concrete cubes from the debris area of the Concrete Laboratory of the School of Housing, Building, and Planning, Universiti Sains Malaysia, Penang. Jaw crushers were used to crush and to break down the concrete waste into smaller particle sizes. After crushing, the RCAs were graded to the required particle sizes using a vibrator sieve to obtain aggregates with maximum sizes of 20 mm. Uncrushed, locally sourced, quartzitic natural river sand with a fine modulus of 3.45 was used as the fine aggregate. Table II shows the sieve analysis of the fine and coarse aggregates that were used in this study, which were graded according to BS 812- Part 103.1 [14].

B. Surface Treatment of RCA

Prior to the surface treatment of RCA, the coarse RCA was first completely dried in an oven for 24h at 105°C. The CM solution was then prepared by dissolving CM (in powder form) at 10% by weight in distilled water. The mixture was stirred for several minutes to ensure the proper dispersion of the CM particles. The dried coarse RCA was then immediately added to the solution. The RCA particles were soaked in the CM solution for 24h to increase the CM absorption. After immersion, the aggregates were drained for 10 min, before they were arranged on a tray to prepare the required moisture states.

TABLE I
TYPICAL CHEMICAL COMPOSITION OF ORDINARY PORTLAND CEMENT AND CALCIUM METASILICATE

Chemical composition	Mass (%)	
	Cement	Calcium Metasilicate
SiO_2	16	50.32
Al_2O_3	3.6	0.77
Fe_2O_3	2.9	0.33
CaO	72	44.44
MgO	1.5	1.31
K_2O	0.34	0.15
P_2O_5	0.06	0.08
MnO	0.03	0.05
TiO_2	0.17	0.03
Others	3.41	2.52
Loss on ignition	2.53	4.6

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

C. Mix Design

The Department of Environment (DOE) method [15] was used to design the concrete mixes with target slump between 30 mm and 60 mm. The mixes were prepared with an effective w/c ratio of 0.41 and the cement content was kept constant at 537 kg/m^3 across all concrete mixtures. The concrete mixtures were prepared by combining the coarse natural aggregates and coarse RCA in proportions of (1) 50% of treated RCA with 50% natural aggregates, or (2) 100% RCA. In this study, the moisture states of fine and coarse natural aggregates for all mixes were used at the as-received moisture state. Only the moisture content of the coarse RCA was controlled after treatment process in different states before it was uses in concrete mix, as described below:

Saturated surface-dried (SSD) – After surface treatment, the aggregates were prepared by draining for 6h (at 28°C ± 1°C), prior to use in concrete mix.

Oven-dried (OD) – The treated aggregates were prepared by drying in a 105°C oven for 24h. The aggregates were then cooled down to room temperature before mixing in concrete.

Air-dried (AD) – The treated aggregates were allowed to dry in a laboratory-controlled environment (at 28°C ± 1°C) for 2d before use.

To maintain a uniform mix design, the actual quantity of water was calculated and adjusted according to the actual moisture content and water absorption capacity of the respective RCA in the concrete mix. Thus, the additional water added to the concrete mix was calculated to correspond with the saturated level of the respective RCA. The additional water was likewise adjusted by taking into consideration the composition and amount of aggregates that were incorporated in the concrete. Table IV summarizes the moisture content of the coarse and fine aggregates prepared for concrete mixes. Meanwhile, the components of all concrete materials, including the actual amount of water required for all mixes, are listed in Table III.

D. Testing

The density and water absorption of natural and treated coarse RCA were tested according to BS 812: Part 2 [16], whereas their moisture content was tested according to BS 812: Part 109 [17].

The workability of the fresh concrete was measured in terms of the slump, which was noted immediately after complete concrete mixing. The slump test was conducted according to BS EN 12350-2 [18]. In this test, the initial slump of fresh concrete was first measured. To determine the slump loss, the slump value was then measured every 15min, as described by Poon et al. [3]. In the present study, the total slump testing period was set to 120min. The recorded room temperature was 27°C ± 2°C during testing.

The compressive strength of hardened concrete from each mix proportion was determined by crushing 100mm-sized concrete cube specimens at 7, 14, and 28d after mixing. Three specimens were tested at each curing age and the average strength was reported. This test was performed according to BS EN 12390-3 [19]. The bulk densities of hardened concrete were determined according to the methods in BS EN 12390-7:2009 [20].

III. Results And Discussion

A. Physical Properties of Natural Coarse Aggregates and Treated Coarse RCA Materials

The physical properties of coarse natural aggregate (granite), coarse untreated RCA (before treatment), and treated coarse RCA (after treatment) were compared by analyzing their particle density and water absorption. The results of the particle density and water absorption tests are shown in Table V. Based on these experimental results, the particle density of the original (untreated) RCA at nominal sizes of 20 and 10mm were found to be 2.33 and 2.23mm, respectively. These figures are lower than the particle density of the coarse natural aggregates, which were 2.60 and 2.58mm for particle sizes of at 20 and 10mm, respectively. RCA was found to be significantly more water-absorbent than the coarse natural aggregates by approximately seven- and eightfold for aggregate sizes of 20 and 10mm, respectively. The low specific gravity and high water absorption of RCA were caused by the old mortar residues attached to the RCA, which are light and porous in nature [21], [22].

TABLE III
Mix Proportions of Concrete Mixtures

Notation of mix	% treated coarse RCA	Proportions (kg/m^3)						
		Water	Cement	Sand	Natural Granite		Treated RCA	
					20mm	10mm	20mm	10mm
SSD-A	50	230	537	693	307	153	307	153
OD-A	50	246	537	693	307	153	307	153
AD-A	50	238	537	693	307	153	307	153
SSD-B	100	228	537	693			613	307
OD-B	100	262	537	693			613	307
AD-B	100	245	537	693			613	307

TABLE IV
Moisture Contents of Aggregates

Notation of mix	Moisture state of treated coarse RCA	Moisture content (%)				
		Sand	Natural Granite		Treated RCA	
			20mm	10mm	20mm	10mm
SSD-A	SSD	0.30	0.16	0.13	3.96	4.58
OD-A	Oven Dry	0.14	0.23	0.14	0.00	0.00
AD-A	Air Dry	0.17	0.20	0.17	1.66	3.14
SSD-B	SSD	0.11			3.96	4.58
OD-B	Oven Dry	0.10			0.00	0.00
AD-B	Air Dry	0.14			1.66	3.14

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TABLE V
PROPERTIES OF THE COARSE AGGREGATE

Properties of Aggregate	Sizes of aggregate	Natural Granite	Untreated RCA	Treated RCA
Particle Density - Oven Dry (Mg/m^3)	20 mm	2.60	2.33	2.4
	10 mm	2.58	2.23	2.3
Water absorption (%)	20 mm	0.60	4.44	3.71
	10 mm	0.70	5.58	5.02

However, the properties of RCA were found to slightly improve after surface treatment. The results showed that the coating layer created by CM significantly acted as microfiller to refill the pores and cracks on the RCA surface, thereby improving its properties. The significant improvements in the particle density and water absorption of RCA after surface treatment as compared with those of untreated RCA are recorded in Table V. The particle density of treated RCA with sizes of 10 and 20 mm were slightly increased by approximately 3% as compared with those of untreated RCA. A relationship exists between the aggregate density and water absorption [23]. Consequently the increased density of the treated RCA significantly reduced its water absorption. The results indicated that the absorption of RCA after treatment was significantly reduced by 10% and 16% for aggregate sizes of 10 and 20 mm, respectively.

B. Influence of Different Moisture States of Treated RCA on Concrete Workability

The workability of all concrete mixes was determined using the slump test results, which are illustrated in Fig. 1. From the results, the different moisture states of the coarse aggregates in the concrete mixes influenced the workability of the concrete. The slump values varied with time. The results generally indicated that the initial slump value of each concrete mix was not significantly affected, especially when treated coarse RCA was used at the SSD or AD state. The initial slump value of concrete was likewise shown to be improved for all mixes when the combination of crushed granite and RCA was used. The results in Fig. 1 show that a better initial slump value was obtained in concrete by combining the natural granite with 50% and 100% treated coarse RCA at the SSD and AD states, which had the initial slump values of up to 65 and 70mm, respectively. The higher initial slump values of the mixes were caused by the adjusted amount of water in the mix. In addition the high moisture content of the SSD and AD states of treated RCA have saturated the aggregates, thereby decreasing their absorption capacity and thus, maintaining the amount of free water in concrete during mixing.

The lower initial slump was observed in concrete with the treated coarse RCA in the OD state. As shown in Fig. 1, when the mixes with coarse aggregates were replaced totally by the treated RCA at the OD state, the initial slump of 50 mm had less workability as compared with the other concrete mixes. In fact, the amount of water (262 kg/m^3) that was added to the mix prepared with the treated coarse RCA in the OD state was higher as compared with that of the other mixes. However, only a small change in the initial slump value was obtained. While, effect the combination of 50% treated coarse RCA in the OD state with the natural coarse aggregate has compensate the low decrease in the initial slump results. This phenomenon was due to the higher water absorption capacity in the very dry states of the treated RCA as compared with the natural coarse aggregate and the other moisture states of treated RCA which lead to absorb more water during mixing, thus decreased concrete workability, especially at a greater content. In addition, the larger surface area and pores of CM particles that were adhered to the coarse RCA surface absorbed portions of free water, thereby resulting in the reduced slump of the concrete. The comparison of the slump loss of the concrete mixes versus time is illustrated in Fig. 1. The concrete prepared with a combination of natural coarse aggregates and treated coarse RCA at AD or SSD state can prolong the slump loss. The slump value of the mixes slowly decreases to zero at 120 min after mixing. Consequently, the replacement of the natural coarse aggregate with treated coarse RCA at different moisture states caused significant rapid slump loss in the mix with time (Fig. 1). The inclusion of the 100% treated RCA at the OD state in the concrete mix had the fastest slump loss as compared with other mixes using 100% treated RCA at the SSD and AD states. The slump of the mix with the OD state was completely lost at 90min after mixing. This result is due the absorption of water by the dry treated RCA, which rapidly reduced the amount of free water in the mixture.

C. Density

The density of hardened concrete containing different proportions of treated coarse RCA at different moisture states is illustrated in Fig. 2. The bulk densities of hardened concrete mixes were generally decreased with the increasing replacement ratio of the coarse aggregate by the treated coarse RCA, regardless of the moisture state of aggregate. Fig. 2 shows that the density of all concrete mixes containing 50% treated coarse RCA (SSD-A, OD-A, and AD-A) are relatively higher as compared with those containing 100% treated coarse RCA (SSD-B, OD-B, and AD-B). This result can be attributed to the presence of adhered mortar, which lowers specific gravity of treated coarse RCA as compared with that of the natural coarse aggregate. This result agrees with that of a previous study [24]. However, when the densities of the concrete mixes are compared according to the different moisture states of the treated coarse RCA, the moisture state significantly influences the density of the hardened concrete. After the substitution of coarse aggregates by 50% or 100%, the density of concrete with the treated coarse RCA at the SSD state is lower than the concretes with the treated coarse RCA at the OD and AD states (Fig. 2). This result may be attributed to the high water content inside the RCA and/or CM grains at the SSD state were lost due to the release after mixing to consume for cement hydration and/or evaporation into air, which lowers the concrete density. The density of concrete mixes containing the treated coarse aggregates at the OD and AD states are slightly similar.

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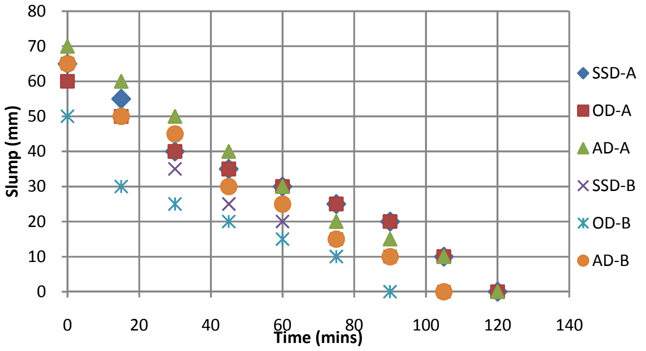

Fig. 1 Slump of concrete mixes versus time

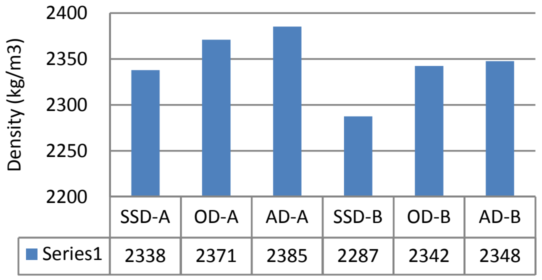

Fig. 2 Density of hardened concrete

D.Compressive Strength

Compressive strength of all concrete mixes in SSD-A, OD-A, AD-A, SSD-B, OD-B, and AD-B were tested at 7, 14, and 28 d after mixing. The variations in compressive strength development of concrete are illustrated in Fig. 3. The different moisture states of the treated coarse RCA at different proportions in concrete mixes influenced the mechanical strength of the concrete.

The compressive strength development for all concrete mixes was increased by increasing the curing age of concrete. From the given mix proportion, the OD-A and the SSD-A concrete mixes exhibited the highest compressive strength development at 7 and 14d of curing, respectively, as compared with the other concrete mixes. At 28d, the strength of the concrete prepared with combination 50% treated coarse RCA at the OD state with natural coarse aggregate (OD-A mix) notably reached 51.67 MPa, which was 3% higher than the mix strength target of 50 MPa. Meanwhile, the similar combination of 50% treated coarse RCA at the AD and SSD states with natural coarse aggregate (AD-A and SSD-A) had a compressive strength of had approximately 48.76 and 47.71 MPa, respectively, which were 2.5% and 4.6% below the mix strength target at 28 d. Although the compressive strength of the AD-A and SSD-A concrete mixes did not achieve the mix strength target, the percentage reduction in the strength of both concrete mixes were relatively small. Previous studies have reported that increasing the replacement of coarse aggregates with normal (untreated) coarse RCA in the concrete mix at the same proportion to 50% produces a maximum decrease of up to 15% less than the strength design target [25]. Therefore, this study has proved that the use of CM as a surface treatment agent for the treated coarse RCA can positively contribute to enhancing the compressive strength of concrete.

However, the results revealed that increasing the replaced amount of coarse aggregate to 100% treated coarse RCA in the concrete mixture decreased the compressive strength of concrete. As Fig. 3 shows, the compressive strength test results at 28d of curing in the OD-B, AD-B, and SSD-B mixes are approximately 9% to 11% lower than the mix strength target of 50 MPa. The compressive strength of the 100% treated coarse RCA was slightly lower than concrete mixes prepared by the combination of 50% treated coarse RCA and natural coarse aggregate, even though the concrete mixes used similar moisture states of coarse aggregate. This trend was similarly observed by previous studies when normal RCA was used to fully replace natural coarse aggregate to produce concrete [25], [26]. This trend can be attributed to the low mechanical strength of RCA as compared with that of the natural aggregates. The high amount of adhered cement mortar that is attached to RCA had relatively higher porosity and weaker strength than the natural aggregate. Thus, an increase in the replacement content ratio of natural coarse aggregate by RCA significantly reduced the compressive strength of the concrete. In this study, the concrete with 100% treated RCA at the OD state has a compressive strength of 45.65 MPa, which is still higher than that of mixes with treated RCA at the AD and SSD states at 28d.

This study demonstrated that the use of different moisture states of coarse RCA after surface treatment significantly influences the compressive strength development of concrete. Concrete mixtures prepared with treated coarse RCA in the OD state, either at 50% or 100% replacement of coarse aggregates, produced higher compressive strength than the other mixtures prepared with treated coarse RCA in the AD and SSD states. The actual amounts of water added to concrete during mixing was higher for the mixes prepared with treated coarse RCA at OD the state as compared with the other mixes. However, the additional water did not seem to affect the concrete porosity. The analysis of the test results attributed the improved strength of these concrete mixes to the following reasons: (i) The interface transition zone (ITZ) at the region between the aggregate and the cement paste determines the mechanical strength properties of concrete [27]. The CM particles adhered to coarse RCA surface in the OD state absorbed the free water during mixing and decreased the w/c ratio at ITZ. Thus, bleeding in the concrete mix is reduced, which produces a stronger and dense interface bond between the cement paste and the coarse aggregate and consequently increases the concrete strength. (ii) The increased hydration of the cement paste is caused by internal curing. The pore structures in coarse RCA and in the CM particles absorb and hold a certain amount of free water into its pores during mixing. This water becomes a self-curing agent for concrete, such that the release of water from pores at later stages can be used for the cement hydration process, thereby increasing the compressive strength of concrete. A similar phenomenon was previously reported for the use of recycled aggregates [28],

[29] and/or other types of pozzolanic materials [30] in concrete strength development. (iii) The reaction of the CM particles and cement, which converts calcium hydroxide into CM hydrate, can enhance the ITZ between the aggregate and the cement paste.

	7 days	14 days	28 days
SSD-A	38.78	47.40	47.71
OD-A	41.64	46.74	51.67
AD-A	39.29	43.13	48.76
SSD-B	36.81	43.26	44.64
OD-B	38.73	41.12	45.65
AD-B	37.53	40.17	45.53

Fig. 3 Development of compressive strength of concrete mixes

The lower concrete compressive strength, especially in concrete mixes prepared with treated coarse RCA at the SSD state is attributed to the bleeding of concrete. The moisture content results of the aggregates in Table III revealed that the moisture content of treated coarse RCA at the SSD state is relatively high as compared with the other RCA, such that it reached saturation. At this level, the additional water in the concrete mix may not be fully absorbed by either the aggregates or the CM particles. The high water inside RCA particles may exit and shift towards the cement matrix during concrete vibration [3]. These factors increase the w/c ratio in the concrete mix and enhance the water film accumulation at the ITZ, thereby inducing concrete bleeding. Thus, the bonds between cement paste and aggregates decrease, which then lowers the concrete strength.

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