Micro-structural analysis of recycled aggregate concrete produced from two-stage mixing approach

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Abstract

Owing to the shortage of space for land reclamation in Hong Kong, it is difficult to dispose of tons of masonry waste generated daily from construction activities. Adoption of recycled aggregate from concrete waste thus becomes a burning issue. The Hong Kong SAR Government has set up a recycling plant in Tuen Mun Area 38 aiming at turning concrete waste into recycled aggregate with a practice note and specifications issued for controlling the quality of recycled aggregate. However, the use of recycled aggregate concrete to high grade applications is rarely reported because of its poorer compressive strength and high variability in mechanical behavior. This paper proposes a new approach in mixing concrete, namely “two-stage mixing approach (TSMA)”, intended to improve the compressive strength for recycled aggregate concrete and hence lower its strength variability. Based upon experimental works, improvements in strength to recycled aggregate concrete were achieved. The effect can be attributable to the porous nature of the recycled aggregate and hence the pre-mix process can fill up some pores and cracks, resulting in a denser concrete, an improved interfacial zone around recycled aggregate and thus a higher strength when compared with the traditional mixing approach.

Keywords: Compressive Strength, Two-stage Mixing Approach, Recycled Aggregate

1. Introduction

As sustainability is a pressing issue all over the world, the word “recycle” forms one of the most important keywords today [1]. Recycling and resource saving have been advocated in the construction industry, but the effectiveness of these has been constrained because the conditions in applying these approaches were not provided [2]. These conditions include the lack of site space and equipment for waste sorting, experience in waste recycling operations, trained supervisors and employees, knowledge of secondary materials markets, environmental and safety regulations.

In Denmark, Netherlands and Japan, there have been records of eighty, seventy-five and sixty-five percent of recycling rates [3-5]. To achieve these rates, special site arrangements such as selective demolition need to be implemented. Different types of materials (bricks and masonry, roofing tiles, concrete and timber) need to be removed separately as much as possible [5] and sorted at the source to facilitate recycling. Recovery of materials from these wastes can reduce the consumption of landfill areas and natural gravel resources. Although the recycling rate is high in some countries, the use of recycled aggregate (RA) is confined to low grade applications such as unbound road base, fill and hardcore. For higher grade applications, new recycling technology needs to be developed. In Japan, higher-grade utilization of concrete has been recorded, leading to a recycling rate of 65% for concrete [5]. One of these is the use of RA as aggregate for new structural concrete. Similarly, in the United Kingdom, it is the government policy to increase the level of RA to promote natural resources conservation and improve environmental protection [6].

The use of recycled aggregate has been strongly advocated in Hong Kong [6-10]. Various government departments have been encouraging adoption of recycled aggregate. The Civil Engineering Department of the Hong Kong Special Administrative Region (HKSAR) has set up a recycling plant to produce recycled aggregate in Tuen Mun Area 38; the Buildings Department of HKSAR has issued a practice note on “Use of recycled aggregates in concrete”; and the Environment, Transport and Works Bureau has published a Technical Circular (Ref: 12/2002) entitled “Specifications facilitating the use of recycled aggregates”. All aims at promoting the use of recycled aggregate and setting standards and practice guidelines for the product. The Architectural Services Department of HKSAR has examined the possibility of using 20% recycled aggregate for project development and the Hong Kong Housing Authority of HKSAR and local universities are finding ways to improve the quality of recycled aggregate. Under the above context, this paper aims to achieve the following objectives:

- i) Examining the current practices in the applications of recycled aggregate concrete (RAC);
- ii) Proposing the two-stage mixing approach (TSMA) to improve the quality of RAC;
- iii) Experimenting the TSMA and assessing the benefits possibly gained; and
- iv) Conducting micro-structural analyses to explore the mechanism of TSMA.

2. Recycled Aggregate Concrete

As revealed from previous studies, the quality of aggregate is commonly classified according to the absorption rates [11]. High absorption indicates high level of cement mortar attachment, which generally leads to concrete with inferior strength, durability and deformation and shrinkage properties. Accordingly, the maximum allowable design strength and the members and portions to which such concrete may be applied are limited. From the research of [11], three types of RA are classified: Type C1, C2 and C3 for recycled coarse aggregate and Type

F1 and F2 for recycled fine aggregate (see Table 1). For the recycled coarse aggregate, Type C1 has the best quality with the lowest water absorption rate of 3% or less and sulfate soundness of 12% or less, while recycled coarse aggregate Type C3 is designed to have 7% or less of water absorption. For the recycled fine aggregate, Type F1 and F2 are designed to have 5% or less and 10% or less of water absorption respectively.

From these three types of recycled coarse aggregate: C1, C2 and C3 and two types of recycled fine aggregate: F1 and F2, four types of suggested RAC applications are recommended for civil and building works as tabulated in Table 2. Among the three types of civil engineering applications of RAC, namely CI, CII and CIII with respect to different combinations of recycled coarse aggregate and recycled fine aggregate (see Table 1), Type CI RAC can be designed up to 18 to 24 MPa, thus suitable for reinforced and plain concrete, lower structure of bridges, tunnel lining and retaining walls. The four types of building work applications of RAC, namely BI, BII, BIII and BIV (see Table 1) can all be designed with a strength of 18 MPa or higher, for various types of application including ordinary reinforced concrete building structures, foundations, foundation slabs and backfilling concrete respectively. Several potential areas in the application of recycled material are tabulated in Table 3.

3. Materials and Methods

Since there are many unsolved problems encountered in controlling the quality of RAC, which include low compressive strength, wide variability of quality, high drying shrinkage, large creep and low elastic modulus [11-12], applications of RAC are hampered. These problems are mainly resulted from the following two reasons:

- Concrete wastes are always contaminated with foreign materials; and
- Recycled aggregate particles are always attached with substantial amount of

Under normal situations, some modifications to the mix proportion are needed in the production of RAC, which can then be produced with the same production procedure as the conventional concrete does. However, such an approach will produce concrete with poorer quality, depending directly on the proportion of RA added. Hence, most studies recommend a limit of 30 percent of RA [14]. Many researchers have successfully applied RA on pavement and roadwork [15-17] or simple structures, underground structures, foundations, piles, and mass concrete [18]. However, its application to higher-grade concrete is not common.

These weaknesses of RA, including high porosity, high amount of cracks, high level of sulphate and chloride contents, high level of impurity and high cement mortar remains, will affect the mechanical performance of RAC [19]. The pre-requisite in applying RA to high grade concrete is to overcome these weaknesses. A new mixing approach: Two-Stage Mixing Approach (TSMA) is proposed. For NMA, the mixer is firstly charged with about one half of coarse aggregate, then with fine aggregate, then with cement and finally with the remaining coarse aggregate. Water is then added immediately before the rotation of the drum or starting the pan [20], while TSMA divides the mixing process into two parts and proportionally splits the required water into two which are added at different timing. Figure 1 illustrates the TSMA mixing procedure while Table 4 shows the symbols used.

The RA adopted in experimenting NMA and TSMA collected from Tuen Mun Area 38 recycling plant has water absorption values of 1.65% for 20mm and 2.63% for 10mm aggregate; while the moisture contents are 0.33% and 0.49% for 20mm and 10mm

respectively according to BS 812: Part 109 [21]. The quality of RA is weaker than that of virgin aggregate (water absorption of virgin aggregate at only 0.77% and 0.57% for 20mm and 10mm respectively), indicating that the major weakness of RA is its high porosity.

As most studies recommend a limit of 30% percentage of RA used, 0%, 10%, 15%, 20%, 25% and 30% of RA have been experimented using the NMA and TSMA with the designated mix proportions according to the specifications of Buildings Department (BD) [22] with a water to cement ratio of 0.45 (see Table 5). The compressive strengths of the mixes are then compared, which is one of the most important mechanical properties of concrete in concrete mix design. 100mm sized cubes are used for testing compressive strength development under the standard curing conditions for 7, 14, 28 and 56 days. Three cubes of 7, 14, 28 and 56 days were tested and the average was taken according to BS 1881: Part 116 [23].

4. Results and Discussion

All the mix proportions of recycled aggregate concrete using TSMA and NMA are controlled with slump of 75mm as required by BD [22]. The results of compressive strengths and the percentages of improvement in different proportions of RA using NMA and TSMA are tabulated in Table 6 with the improvement trends for 7-day, 14-day, 28-day and 56-day strengths shown in Figures 2 to 5 respectively. As shown in Figures 2 to 5, a clear strength enhancement in using TSMA can be found when compared with that of NMA. In general, gradual improvements in strength with increased percentages of RA can be observed when using TSMA.

Concrete is of a three-phase system, comprising coarse aggregate, mortar matrix with fine aggregate, and interfacial zones (ITZ) between coarse aggregate and the mortar matrix [24-

26]. In concrete, the interfacial zone between cement paste and aggregate plays a critical role. At the macroscopic level, concrete is a composite material consisting of discrete aggregates dispersed in a continuous cement-paste matrix [27]. As with other composites, the bond between these two major components of concrete critically determines the mechanical performance.

Though the ITZ itself is quite narrow, it occupies a relatively large proportion of the cement paste. In a typical concrete composite, the mean spacing between aggregate particles is 75 to 100 μ m. Assuming a 40 μ m thickness for the ITZ, it has been estimated that the ITZ makes up 20 to 40 percent of the total volume of the cementitious matrix [28]. The weakness of the interfacial zone inhibits the achievement of composite action in normal strength concrete [29]. Hence, the interfacial region is generally regarded as the ‘weak link’ in concrete [30-35].

In fact, the structure of RAC is much more complicated than that in normal concrete. RAC possesses two ITZs, one between the RA and new cement paste (new ITZ), and the other between the RA and the old mortar attached (old ITZ), which are schematically shown in Figure 6. The cement mortar remains at the ITZ of RA form the weak link in RAC, which is composed of many minute pores and cracks and they critically affect the ultimate strength of the RAC. These pores and cracks increase consumption of water leading to less water for hydration at the ITZ of RAC.

During the first stage of mixing, TSMA uses half of the required water for mixing leading to the formation of a thin layer of cement slurry on the surface of RA which will permeate into the porous old cement mortar, filling up the old cracks and voids. At the second stage of mixing, the remaining water is added to complete the concrete mixing process. Under the

examination of scanning electron microscopy (SEM), the cracks within RA are filled after adopting TSMA (see Figure 7), while similar cracks in RA still remain unfilled for NMA (see Figure 8). Further, more voids and cracks are found between RA and mortar for NMA (see Figures 9 and 10) since complete hydration of the mortar at ITZ is hampered due to inadequacy of water. Figures 11 and 12 show the SEM photography of the dense and loose cement paste mixed by TSMA and NMA respectively.

The experiments show that the two-stage mixing approach can enhance the compressive strength of RAC by developing a stronger interfacial zone. The quality of ITZ depends on surface characteristics of the aggregate particles, the degree of bleeding, chemical bonding and the specimen preparation technique which, however, are notoriously difficult to measure. Although these effects have been reported by some investigations, the results are difficult to reconcile. Nonetheless, it is generally agreed that as the paste-aggregate bond strength increases, the concrete strength also increases [28].

Under the examination of SEM, both the new interfacial zone and old interfacial zone of RAC are identified. Figure 13 shows a stronger and denser new interfacial zone in RAC after adopting TSMA, compared to the poorer ITZ for NMA shown in Figure 14. Figure 15 shows a stronger and denser old interfacial zone around RA after adopting TSMA, compared to the old ITZ for NMA as shown in Figures 16 and 17. It is clearly seen that both the new and old interfacial zones for TSMA are stronger than those for NMA. Therefore, the two-stage mixing approach can improve the ITZ of RA and thus the compressive strength of the RAC. Figure 18 illustrates the concrete matrix scenario for TSMA schematically.

5. Conclusion

The poor quality of RAC resulted from the higher water absorption, higher porosity, weaker ITZ between RA and new cement mortar hampers the application of RAC for higher grade applications. In this study, the two-stage mixing approach is proposed to strength the weak link of RAC, which is located at the interfacial transition zone (ITZ) of the RA. The two-stage mixing approach gives way for the cement slurry to gel up the RA, providing a stronger ITZ by filling up the cracks and pores within RA. From the laboratory experiments, the compressive strengths have been improved. This two-stage mixing approach can provide an effective method for enhancing the compressive strength and other mechanical performance of RAC and thus the approach opens up a wider scope of RAC applications.

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Table 1: Quality Standard of Recycled Aggregate Concrete for Public Works [11]

Type	Recycled Coarse Aggregate (2)			Recycled Fine Aggregate		
	Type C1	Type C2		Type C3	Type F1	Type F2
Absorption (%)	3 or less	3 or less	5 or less	7 or less	5 or less	10 or less
Sulfate	12 or less	40 or less	12 or less	-	10 or less	-
Soundness (%)		40 or less (1)				
Notes:						
(1) Where freezing and thawing resistance is not required;						
(2) Grading and content of injurious impurities are also stipulated.						

Table 2: Types of Recycled Aggregate Concrete and Suggested Uses in Civil and Building Works [11]

Civil Works Applications				
Type	Coarse Aggregate	Fine Aggregate	Suggested Design Strength (MPa)	Suggested Use of Recycled Aggregate Concrete
CI	Recycled Coarse Aggregate Type C1	Normal Fine Aggregate	18 to 24	Reinforced or plain concrete; lower structure of bridges, tunnel lining, retaining walls, etc.
CII	Recycled Coarse Aggregate Type C2	Normal or Recycled Fine Aggregate Type F1	16 to 18	Plain concrete; masonry units, bases for road attachment, gutters, gravity type retaining walls, etc.
CIII	Recycled Coarse Aggregate Type C3	Recycled Fine Aggregate Type F2	Less than 16	Subslab concrete, back filling concrete, leveling concrete, etc.
Building Works Applications				
BI	Recycled Coarse Aggregate Type C1	Normal Fine Aggregate	18 or more	Ordinary reinforced concrete buildings
BII	Recycled Coarse Aggregate Type C2	Normal Fine Aggregate	18 or more	Concrete attached to ground; foundation, cast-in-place concrete piles, concrete slabs on steel decks, etc.
BIII	Recycled Coarse Aggregate Type C2	Recycled Fine Aggregate Type F1	18 or more	Foundation slabs, earthen floor slabs, subslab concrete, back filling concrete, leveling concrete, etc.
BIV	Recycled Coarse Aggregate Type C3	Recycled Fine Aggregate Type F2	18 or more	Subslab concrete, back filling concrete, leveling concrete, etc.

Table 3: Potential Areas of Application of Recycled Materials [33]

Recycled Material	Use	Areas of Application
Crushed Concrete	As Aggregate	Concrete Roads and Aprons
		Drainage Work
		Shallow Storage Tanks
		Pipes and Culverts
		Sewage / Water Treatment Plants
		Permeable Backing to Earth Retaining Structures
		Bedding Materials to Reinforced Concrete Structures
Crushed Concrete / Brick		Building Partition Walls
		Floors and Foundation
		Garbage / Refuse Disposal Plant
Crushed Concrete	As Aggregate in New Asphalt	Base Course Materials in Pavement
Crushed Concrete / Brick	As Unbound Base Course	Runways, Taxiway and Aprons
		Parking Lots and Other Yards
Crushed Concrete / Brick or Recycled Aggregate (<4.75mm)	As Fill Material	Cable Trenches

Table 4: Symbols Used for Representing Various Materials

Fine Aggregate	Water	Recycled Aggregate + Natural Coarse aggregate

Half of the required Water	Cement	Concrete

Table 5: Mix Proportions

Ingredients of concrete	Mass (in kg)
Ordinary Portland cement	100
Fine aggregate	180
20mm coarse aggregate	180
10mm coarse aggregate	90

Table 6: Compressive Strengths and Percentages of Improvement in Different Proportions of
RA Using NMA and TSMA

Mixing Methods		Normal Mixing Approach (days)				Two-Stage Mixing Approach (days)				Improvement % (days)			
		7	14	28	56	7	14	28	56	7	14	28	56
Compressive Strength (MPa)	0%	43.87	53.01	55.72	67.60	45.0	54.0	56.0	68.0	2.59%	1.86%	0.51%	0.59%
	10%	50.29	54.53	58.98	74.60	54.0	61.4	64.5	79.2	7.41%	12.62%	9.41%	6.18%
	15%	45.14	51.72	56.26	70.19	49.6	55.7	61.3	72.4	9.83%	7.67%	8.88%	3.15%
	20%	42.21	51.92	53.68	68.84	45.1	56.6	65.1	72.0	6.96%	9.02%	21.19%	4.64%
	25%	51.09	52.62	52.31	67.23	53.0	57.1	63.1	77.7	3.82%	8.44%	20.64%	15.61%
	30%	45.49	54.58	58.07	72.78	54.8	60.6	66.2	77.5	20.46%	11.05%	13.94%	6.44%

(i) NMA

(ii) TSMA

Figure 1: Mixing Procedures of the (i) Normal Mixing Approach and

(ii) Two-Stage Mixing Approach

Figure 2: 7-day Compressive Strengths Using Normal Mixing Approach and Two-Stage Mixing Approach

Figure 3: 14-day Compressive Strengths Using Normal Mixing Approach and Two-Stage Mixing Approach

Figure 4: 28-day Compressive Strengths Using Normal Mixing Approach and Two-Stage Mixing Approach

Figure 5: 56-day Compressive Strengths Using Normal Mixing Approach and Two-Stage Mixing Approach

Figure 6: Interfaces of Recycled Aggregate

Figure 7: Filled Crack in RA using TSMA

Figure 8: Unfilled Crack in RA using NMA

Figure 9: Crack in RA using NMA

Figure 10: Voids in RA using NMA

Figure 11: Dense Cement Paste for TSMA

Figure 12: Loose Cement Paste for NMA

Figure 13: New Interfacial Zone for TSMA

Figure 14: Poorer New Interfacial Zone for NMA

Figure 15: Old Interfacial Zone for TSMA

Figure 16: Old Interfacial Zone for NMA

Figure 17: Old Interfacial Zone for NMA

Figure 18: RA Structure after Adopting TSMA