A paper submitted to

Magazine of Concrete Research

By

Comparing Performance of Modified Two-Stage Mixing Approach for Producing Recycled Aggregate Concrete

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March 2006

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Abstract

Exhaustion of landfill areas coupled with the extensive redevelopment programme in Hong Kong has prompted the use of recycled aggregate. However, the inferior quality of recycled aggregate (RA) has restricted its use to low grade applications such as roadwork sub-base and pavements, while its adoption for higher grade concrete is rare because of the lower compressive strength and higher variability in mechanical performance of RA. A new concrete mixing method: two-stage mixing approach was advocated to improve the quality of recycled aggregate concrete by splitting the mixing process into two. This paper describes two modified mixing methods with some alteration to the two-stage mixing approach by proportioning ingredients of cement and water with the percentage of RA added in the first mix, named as two-stage mixing approach$_{(proportional\ 1)}$ ($TSMA_{p1}$) and proportioning the cement content (without water) with the percentage of RA used in the first mix, named as two-stage mixing approach$_{(proportional-2)}$ ($TSMA_{p2}$). Based on experimental works and results, improvements in strength to RAC were achieved with both $TSMA_{p1}$ and $TSMA_{p2}$. This can be attributable to the porous nature of RA and the pre-mixing process that fills up some of its pores and cracks, resulting in a denser aggregate and concrete. An improved interfacial zone around RA with lower water/cement ratio generated from $TSMA_{p2}$ without changing the ultimate water/cement ratio gives a higher strength than the normal mixing approach (NMA) and $TSMA_{p1}$.

Keywords: Two-Stage Mixing Approach, Proportional Mixing, Recycled Aggregate Concrete, Waste Management, Construction

Introduction

Construction wastes in Hong Kong have an average growth rate of two to four percent per annum [1]. At the high tide of implementing sustainable construction, the efforts of practicing environmental management in construction business have been rapidly growing. For facilitating the implementation of waste management and sorting of C&D waste in Hong Kong, the Environment, Transport and Works Bureau (ETWB) has issued a technical circular on "Waste Management on Construction Sites" appealing for sorting various types of materials before sending out from construction sites, including all excavated materials, metals, cardboard and paper packaging, plastics, and chemical wastes. The Hong Kong Housing Authority (HKHA) has trial implemented selective demolition in a school demolition project at Lower Ngau Tau Kok Phase 1 Estate, in which different types of materials are sorted, including timber, steel, florescent tubes, electricity fittings, toilet sets, red bricks, tile, finishes, drainage pipes, cable, etc., in order to improve the rates of recycling.

For encouraging the adoption of RA, the Buildings Department of the Hong Kong Special Administrative Region (HKSAR) issued a practice note entitled "Use of Recycled Aggregates in Concrete" in February 2003 [2] in encouraging the adoption of RA for construction activities. Meanwhile, the Civil Engineering Department (CED) of HKSAR has commissioned a pilot recycling plant at Tuen Mun Area 38 with a view to supply RA to a number of public works projects earmarked for such purposes. In the plant, it produces various sizes of RA including Grade 200 (200mm), 40mm, 20mm, 10mm, 5mm and >5mm down with production proportions of 23%, 34%, 12%, 10%, 14% and 7% respectively. These are mainly applied for filling, drainage, roadwork, concrete production and others in proportions of 54.3%, 16.82%, 7.31%, 1.09% and 20.48% respectively.

Under the above context, this paper aims to provide technical guidance to practitioners in improving the quality of recycled aggregate concrete (RAC) by: i) deeper investigation of the two-stage mixing approach (TSMA) developed by Tam *et al* [3]; ii) modification of the proportions and split ingredients in the mixing procedure of TSMA so as to develop two new two-stage mixing methods namely two-stage mixing approach$_{(proportional-1)}$ ($TSMA_{p1}$) and two-stage mixing approach$_{(proportional-2)}$ ($TSMA_{p2}$); iii) experimenting the $TSMA_{p1}$ and $TSMA_{p2}$ and assessing the benefits of each; and iv) analyzing the micro-structural behaviour of $TSMA_{p1}$ and $TSMA_{p2}$.

Recycled Aggregate Concrete

Until recently almost all demolished concrete was thrown away and there is a shortage of landfill areas. Reducing the waste generation is a pressing issue all over the world. Concrete is such an essential, mass-produced material like steel in the construction industry, much effort should be made to recycle and conserve these resources. Recycling of concrete and other building materials during the building process of new buildings and at the end of the life cycle is usually very inadequately arranged. Concrete which is suitable for complete recycling, will allow repeated recycling, as is the case for steel and aluminum [4]. Since concrete is composed only of cementitious materials, even the powders generated during the production of recycled aggregate can be reprocessed as cement resources. This enables concrete to be recycled in a fully closed system, thus enhancing the benefit to the environment. Recycling of concrete demolition waste can provide opportunities for saving resources, energy, time, and money. Furthermore, recycling and controlled management of concrete demolition waste will save the use of land and create better opportunities for handling other kinds of wastes. There are a number of opportunities for utilizing concrete demolition waste apart from dumping. Recycling of concrete can be accomplished by reuse of concrete products, processing into secondary raw materials for use as fill, road bases and sub bases, or aggregate for production of new concrete [5-6]. Economic benefits, reducing environmental impacts and saving resources can be gained in adopting RA [6-10].

Although there are environmental and cost benefits in using RA, the current legislative regulations and experience are not enough to support and encourage recycling demolished concrete for higher grade applications [11-12]. These technical problems include weak interfacial transition zones, porous and transverse cracks on demolished concrete, high level of sulphate and chloride contents, impurity, cement remains, poor grading, lower quality and higher variation in quality [12-35]. The density, compressive strength, modulus of elasticity, flexural strength, tensile strength, splitting tensile strength, bonding strength and shrinkage can be reduced up to 10%, 86.4%, 50%, 16%, 6%, 50.7%, 26% and increased up to 53.4% respectively [35-49]. Details results are summarized in Table 1. The pre-requisite in applying RA to high grade concrete is to overcome these weaknesses.

<Table 1>

Two-Stage Mixing Approach

The Two-stage mixing approach (TSMA) was developed by Tam *et al.* [3] for improving the quality of RAC, in which it divided the mixing process into two parts and proportionally split the required water into two which is added at different timing. First, fine and coarse aggregates are mixed for 60 seconds before half of the water required is added and mixed for another 60 seconds; then cement is added and mixed for 30 seconds before the remaining half of water is added and mixed for 120 seconds.

Improvement of strength is achieved up to 21.19 percent for 20 percent of RA used under 28-

day curing conditions under TSMA [3]. During the first stage of mixing, it 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.

Two-Stage Mixing Approach$_{\textbf{(proportional-1)}}$

The two-stage mixing approach$_{(proportional-1)}$ (TSMA$_{p1}$) is proposed, which divides the mixing process into two parts and proportionally splits the required cement and water with the percentage of RA added in the pre-mix procedure for 60 seconds. The remaining ingredients of concrete are then added and mixed with another 120 seconds.

In this study, the RA adopted was collected Tuen Mun Area 38 recycling plant. Five, ten, fifteen, twenty, twenty-five and thirty percents of RA have been experimented using the normal mixing approach (NMA) and TSMA$_{p1}$ with the designated mix proportions according to the specifications of Buildings Department (BD) of the Hong Kong Special Administrative Region [2] with a water to cement ratio of 0.45 (see Table 2). The compressive strengths, one of the major mechanical properties of concrete mix, were tested by crushing 100mm cubes which are then compared at 7, 14, 28 and 56 days according to BS 1881: Part 116 [50]. The results of compressive strengths in indifferent proportions of RA using NMA and TSMA$_{p1}$ are tabulated in Table 3.

<Table 2>

<Table 3>

Furthermore, the static modulus of elasticity of cylinders in 100mm diameter under 28-day curing conditions was examined based on BS 1881: Part 121 [51]. Three preloading cycles, using the same loading and unloading rate, were recorded, the results are presented in Table 4.

<Table 4>

As shown in Table 3, a clear strength enhancement in using $TSMA_{p1}$ is recorded when compared with that of NMA in different levels of improvement for different percentages of RA used. However, the change in values of the static modulus of elasticity is non-significant to prove any improvement (see Table 4). This phenomenon can be explained by the fact that RA is composed of many minute pores and cracks, especially around the interfacial transition zone (ITZ). During the first stage of mixing, $TSMA_{p1}$ uses proportional contents of cement and water for mixing leading to the formation of a thin layer of cement slurry on the surface of RA that permeates into the porous structure of cement-mortar remains. The difference between TSMA and $TSMA_{p1}$ is that the cement slurry in $TSMA_{p1}$ during the pre-mix procedure is used wholly for covering up the surface of RA rather than for RA and virgin aggregate as the TSMA does. The greatest improvement in strength is recorded at 13.69 percent when 25 percent of RA substitutions under 14-day curing conditions are adopted.

Two-Stage Mixing Approach$_{(proportional\text{-}2)}$

Having studied $TSMA_{p1}$, another modified mixing method: two-stage mixing approach$_{(proportional\text{-}2)}$ ($TSMA_{p2}$), is experimented. $TSMA_{p2}$ follows a similar procedure in mixing as $TSMA_{p1}$ does but with only the required cement proportionally split into two portions for the two stages of mixing without water added in the first stage of mixing for 60 seconds. The remaining ingredients of concrete are then added and mixed for another 120 seconds.

Similarly, from five to thirty percent of RA has been experimented for $TSMA_{p2}$. The compressive strength and the static modulus of elasticity of the mixes are then measured according to BS 1881: Part 116 [50] and BS 1881: Part 121 [51] respectively, in which the results in indifferent proportions of RA using NMA and $TSMA_{p2}$ are tabulated in Tables 3 and 4 respectively.

As shown in Table 3, a clear strength enhancement of $TSMA_{p2}$ can be found when compared with that of NMA. In general, gradual improvements in strength with increased percentages of RA when using $TSMA_{p2}$ can be observed, but with no clear pattern of improvement for the static modulus of elasticity (see Table 4). The greatest improvement is recorded at 20 percent of RA substitution with around 20 percent improvement in 28-days curing.

This situation is similar to that of $TSMA_{p1}$. During the first stage of mixing, $TSMA_{p2}$ uses proportional contents of cement for mixing in forming a thin layer of cement slurry around RA, which help to provide a dense ITZ around the old cement mortar. The $TSMA_{p2}$ helps to fill up partly these pores and cracks by soluble alkaline substances from the cement with a relatively lower water/cement ratio around aggregate when compared with $TSMA_{p1}$ and NMA at the first stage of mixing before exposing the RA for throughout mixing at the second stage. Therefore, the weaker link at the ITZ of concrete can be improved.

Discussions

Since concrete is a composite material, the interfaces between components can be expected to have major effects on its physical properties [52]. In ordinary Portland cement concrete, the interfacial zone between cement paste and aggregate exhibits characteristics greatly different from those of the bulk paste. The addition of mineral admixtures to the mix has been shown to significantly alter the interfacial zone microstructure and enhance physical properties of the composite [53]. At the macroscopic level, concrete is a composite material consisting of discrete aggregates dispersed in a continuous cement-paste matrix [16]. As with other composites, the bond between these two major components of concrete is a critical component determining the mechanical performance. Generally, the mechanical properties of aggregate play a minor role in the mechanical behaviour of normal strength concrete due to the weak interface between the aggregate and matrix phases [26]. The weakness of the interface inhibits the achievement of composite action in normal strength concrete [14-24]. As RA has some cement mortar remains at the interfacial layer, this forms the weak link between the recycled aggregate and new cement mortar [15,20,21,23,28,35].

The $TSMA_{p1}$ aims at developing a stronger interfacial zone for the RA and hence enhancing the strength of the new interfacial transition zone (ITZ); while the $TSMA_{p2}$ is also designed to enhance the interfacial zone as that of $TSMA_{p1}$, but with a lower water/cement ratio around ITZ, which can further improve the ITZ for RA and hence the strength of RAC. From Table 3, it can clearly show that there is an improvement after adopting $TSMA_{p2}$ when compared with $TSMA_{p1}$; up to 12 percent improvement for 20 percent RA substitution in 28-days can be achieved. The bond strength of the new ITZ depends on surface characteristics of the aggregate particles, the degree of bleeding, chemical bonding and the particular specimen preparation technique. However, these are notoriously difficult to measure and are not possible to reconcile the results of the various investigations that have been reported. It is generally found that, as the paste-aggregate bond strength increases, the concrete strength also increases[54]; therefore, the strength characteristic of the RAC depends on the quality of the new ITZ. Figures 1 and 2 show the improved quality of new ITZ from the micrographs of scanning electron microscopy (SEM) on $TSMA_{p1}$ and $TSMA_{p2}$ respectively; both are better than that of NMA (see Figure 3). Hence, both $TSMA_{p1}$ and $TSMA_{p2}$ improve the ITZ of RA and thus the compressive strength of the RAC which provide some alternative methods to TSMA. Figure 4 illustrates the concrete scenario for NMA, $TSMA_{p1}$ and $TSMA_{p2}$ schematically.

<Figure 1>

<Figure 2>

<Figure 3>

<Figure 4>

Conclusion

In order to save the limited landfill areas and provide a good waste management practice, there seems no other option but recycling construction and demolition wastes. However, the poor quality of RAC resulted from the higher water absorption, higher porosity, weaker interfacial zone behaviour between RA and new cement mortar render the application of RAC for higher grade applications difficult. The two-stage mixing approach (TSMA) developed by Tam *et al.* [3] can improve the strength of RAC. This paper has studied two other alternative mixing methods by modifying the pre-mix procedure and altering the ingredients of concrete. $TSMA_{p1}$ gives way for the cement slurry to gel up the RA, providing a stronger ITZ; while $TSMA_{p2}$ provides a layer of cement slurry with a lower water/cement ratio around RA. From the laboratory tests, the compressive strengths of both methods can be improved, in which $TSMA_{p2}$ can achieve a higher improvement when compared with $TSMA_{p1}$. However, there is no significant difference on the static modulus of elasticity between different mixing approaches. The optimal situations occur at 25 percent of RA substitution under 14-day with 13.69 percent improvement for $TSMA_{p1}$ and 20 percent of RA substitution with around 20 percent improvement under 28-day for $TSMA_{p2}$. On the other hand there are nearly no improvements for other percentages of RA and other testing ages. The results show that special mixing procedures like $TSMA_{p1}$ and $TSMA_{p2}$ may provide alternatives for enhancing the performance of RAC to TSMA and thus opening up a wider scope of application for recycled aggregate concrete.

Acknowledgments

The work described in this paper was fully supported by a grant from the Housing Authority Research Fund of the Hong Kong Special Administrative Region, China (Project Ref. No. 9460004).

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Table 1a: Summary on the Previous Researches about the Performance of Recycled Aggregate Concrete

Source(s)	Replacement ratio	Density*	Cube strength*	Modulus of elasticity*	Flexural strength*	Tensile splitting strength*	Shear strength*	Bending strength*	Shrinkage*
Acker [35]	100% replacement of Coarse Recycled Aggregate (CRA)		17.2% lower	23% lower	20% lower				16.7% larger
Ahmad *et al.* [36]	100% replacement of CRA		33% lower		16% lower (at 14 days)				
Bretschneider [37]	100% replacement of CRA			11.9% lower	8.1% lower				
	75% replacement of CRA			4.0% lower					
	50% replacement of CRA			5.8% lower	8.1% lower				
Frondistou-Yannas [38]	100% replacement of CRA		4% to 14% lower	40% lower					
Grubl *et al.*[39]	100% replacement of CRA			28.3% lower					
	75% replacement of CRA			21.9% lower					
	50% replacement of CRA			23.3% lower					
	25% replacement of CRA			13.6% lower					
Hansen and Marga [40]	100% replacement of CRA		30% lower						
Ikeda *et al.* [41]	100% replacement of CRA		15% to 40% lower	30% to 50% lower		6% lower	No change	26% lower	
Notes: * Tests are conduced in the curing of 28 days.									

Table 1b: Summary on the Previous Researches about the Performance of Recycled Aggregate Concrete

Source(s)	Replacement ratio	Density*	Cube strength*	Modulus of elasticity*	Flexural strength*	Tensile strength*	Shear strength*	Bending strength*	Shrinkage*
Kakizaki *et al.* [42]	100% replacement of CRA and Fine Recycled Aggregate (FRA)		32% lower	40% lower					
Masood *et al.* [43]	10% replacement of FRA		20% lower	32.4% lower	4.2% lower	10.6% lower			
	20% replacement of FRA		22.6% lower	22.7% lower	7.3% lower	16.8% lower			
	30% replacement of FRA		25.5% lower	20.2% lower	10.4% lower	50.7% lower			
Nishibayashi and Yamura [44]	100% replacement of CRA		15% to 30% lower	15% lower					
Roos [45]	100% replacement of CRA	10% lower	34% lower	36.4% lower					
Teranishi *et al.* [46]	50% replacement of CRA		57.8% lower	30.5% lower					53.4% larger
Notes: * Tests are conduced in the curing of 28 days.									

Table 1c: Summary on the Previous Researches about the Performance of Recycled Aggregate Concrete

Source(s)	Replacement ratio	Density*	Cube strength*	Modulus of elasticity*	Flexural strength*	Tensile strength*	Shear strength*	Bending strength*	Shrinkage*
Topcu [47]	30% replacement of CRA#		31.8% lower						
	50% replacement of CRA#		45.5% lower						
	70% replacement of CRA#		54.5% lower						
	100% replacement of CRA#		86.4% lower						
Xiao *et al.* [48]	30% replacement of CRA	1.4% lower	5% lower						
	50% replacement of CRA	2.4% lower	17.5% lower						
	70% replacement of CRA	2.4% lower	15.6% lower						
	100% replacement of CRA	5.1% lower	25.6% lower						
Yanagi *et al.* [49]	30% replacement of CRA		0.3% to 11.2% lower	0% to 18.7% lower					0.4% to 30.9% larger
	50% replacement of CRA		1.2% go 16.8% lower	2.8% to 25.1% lower					0.1% to 29.9% larger
	100% replacement of CRA		4.1% to 19.7% lower	1.1% to 25.8% lower					5.9% to 40% larger

Notes: * Tests are conduced in the curing of 28 days;
The quality of these recycled aggregates is poor, with water absorption of 7% in 30 minutes.

Table 2: Mix Proportions

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

Table 3: Compressive Strengths and Percentages of Improvement in Different Proportions of RA Using NMA, $TSMA_{p1}$ and $TSMA_{p2}$

Mixing Methods	% of RA	Compressive Strength (MPa)				Improvement when compared with NMA				Improvement when compared with $TSMA_{p1}$			
		7	14	28	56	7	14	28	56	7	14	28	56
NMA	5%	45.053	53.047	57.263	70.273	-				-			
	10%	50.290	54.527	58.980	74.603								
	15%	45.143	51.717	56.260	70.190								
	20%	42.210	51.920	53.680	68.843								
	25%	51.090	52.617	52.313	67.230								
	30%	45.493	54.577	58.067	72.777								
$TSMA_{p1}$	5%	46.007	56.607	61.620	74.580	2.12%	6.73%	7.61%	6.13%	-			
	10%	51.087	55.287	60.273	74.623	1.59%	1.38%	2.18%	0.02%				
	15%	48.383	53.873	58.380	73.283	7.17%	4.16%	3.77%	4.41%				
	20%	45.263	53.840	57.380	71.377	7.23%	3.70%	6.90%	3.69%				
	25%	52.827	59.820	58.313	75.457	3.40%	13.69%	11.47%	12.24%				
	30%	46.133	55.030	59.303	72.970	1.41%	0.83%	2.14%	0.27%				
$TSMA_{p2}$	5%	46.077	57.207	64.280	75.240	2.29%	7.86%	12.26%	7.07%	0.16%	1.07%	4.32%	0.89%
	10%	52.383	56.340	63.283	76.267	4.16%	3.33%	7.29%	2.24%	2.52%	1.92%	4.99%	2.21%
	15%	51.430	57.377	61.380	74.377	13.93%	10.95%	9.10%	5.97%	6.31%	6.52%	5.14%	1.50%
	20%	46.457	60.167	64.283	77.033	10.05%	15.89%	19.75%	11.91%	2.63%	11.76%	12.03%	7.93%
	25%	55.387	61.280	58.313	76.273	8.41%	16.46%	11.47%	13.46%	4.85%	2.44%	0.00%	1.09%
	30%	51.340	59.343	62.340	75.237	12.86%	8.73%	7.36%	3.38%	11.29%	7.83%	5.11%	3.11%

Table 4: Static Modulus of Elasticity in Different Proportions of RA

Using NMA, $TSMA_{p1}$ and $TSMA_{p2}$

Mixing Methods	% of RA	Modulus of Elasticity [$N(mm^2)^{-1}$]	Improvement when compared with NMA
NMA	5%	31064.507	-
	10%	29729.436	
	15%	30278.800	
	20%	29117.681	
	25%	29303.469	
	30%	28194.175	
$TSMA_{p1}$	5%	33249.626	7.03%
	10%	31257.410	5.14%
	15%	30356.970	0.26%
	20%	33915.371	16.48%
	25%	33000.000	12.61%
	30%	28991.727	2.83%
$TSMA_{p2}$	5%	32221.504	3.72%
	10%	30268.399	1.81%
	15%	30283.425	0.02%
	20%	32232.292	10.70%
	25%	29487.807	0.63%
	30%	31912.355	13.19%