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Microstructural 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 premix 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 concrete; Waste management; Construction

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 80%, 75% and 65% 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

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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 soundness (%)	12 or less	40 or less 40 or less (1)	12 or less	–	10 or less	–

(1) Where freezing and thawing resistance is not required.
(2) Grading and content of injurious impurities are also stipulated.

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 the "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 microstructural 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

Table 2
Types of recycled aggregate concrete and suggested uses in civil and building works [11]

Type	Coarse aggregate	Fine aggregate	Suggested design strength (MPa)	Suggested use of recycled aggregate concrete
Civil works applications				
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.

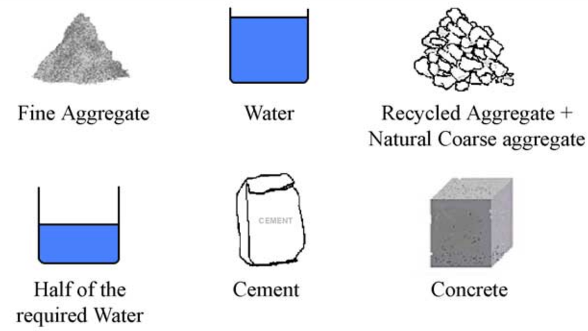
Table 3
Potential areas of application of recycled materials [33]

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 (<4.75 mm)	As fill material	Cable trenches

strength and the members and portions to which such concrete may be applied are limited. From the research in Ref. [11], three types of RA are classified: Types C1, C2 and C3 for recycled coarse aggregate and Types 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, Types 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

Table 4
Symbols used for representing various materials



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 relatively soft cement mortar paste, making these aggregates more porous and less resistant to mechanical attacks [13].

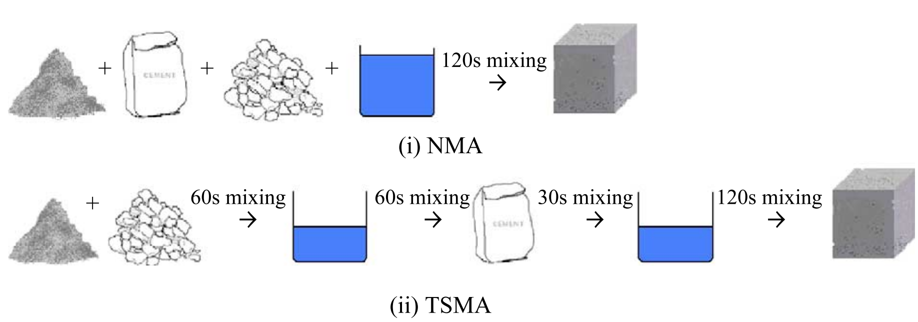


Fig. 1. Mixing procedures of the (i) normal mixing approach and (ii) two-stage mixing approach.

Table 5
Mix proportions

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

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% 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 prerequisite 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. Fig. 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 20 mm- and 2.63% for 10-mm aggregate; while the moisture contents are 0.33% and 0.49% for 20 and 10 mm, 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 20 and 10 mm, respectively), indicating that the major weakness of RA is its high porosity.

As most studies recommend a limit of 30% 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. One hundred-millimeter-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 75 mm, 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-, 14-, 28- and 56-day strengths, as shown in Figs. 2–5, respectively. As shown in Figs. 2–5, 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.

Although 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 μm. Assuming a 40-μm thickness for the ITZ, it has been estimated that the ITZ makes up 20% to 40% of the total volume of the cementitious matrix [28]. The weakness of the interfacial zone inhibits the achievement of

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 percent (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

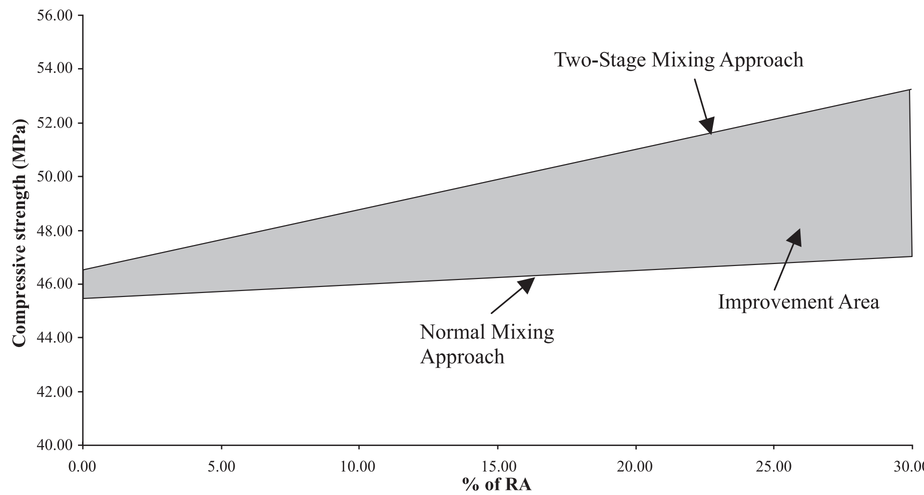


Fig. 2. Seven-day compressive strengths using normal mixing approach and two-stage mixing approach.

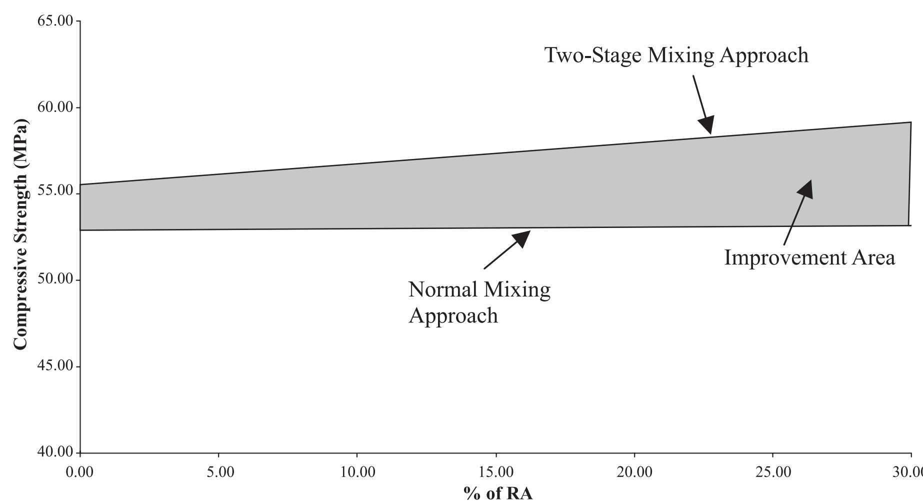


Fig. 3. Fourteen-day compressive strengths using normal mixing approach and two-stage mixing approach.

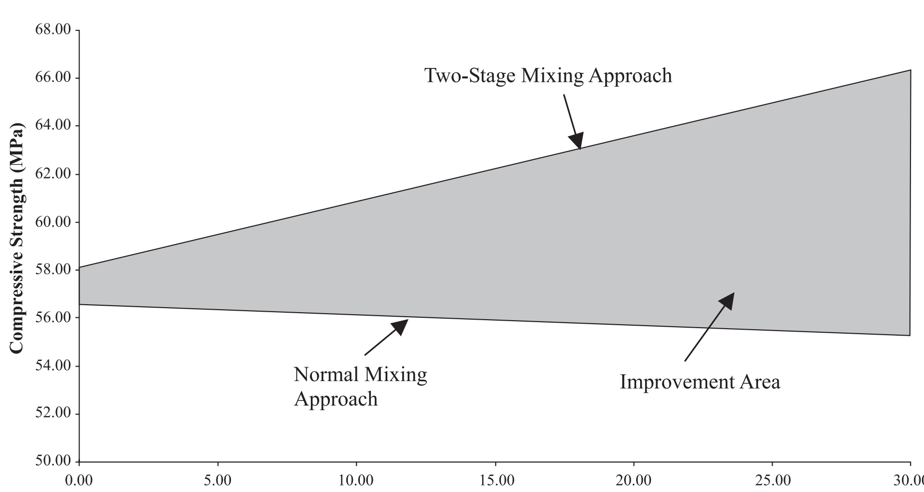


Fig. 4. Twenty-eight-day compressive strengths using normal mixing approach and two-stage mixing approach.

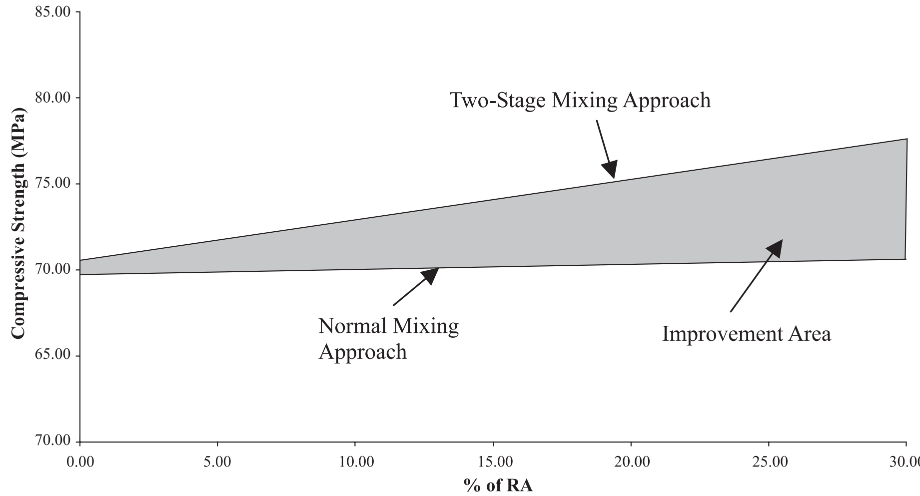


Fig. 5. Fifty-six-day compressive strengths using normal mixing approach and two-stage mixing approach.

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 Fig. 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.

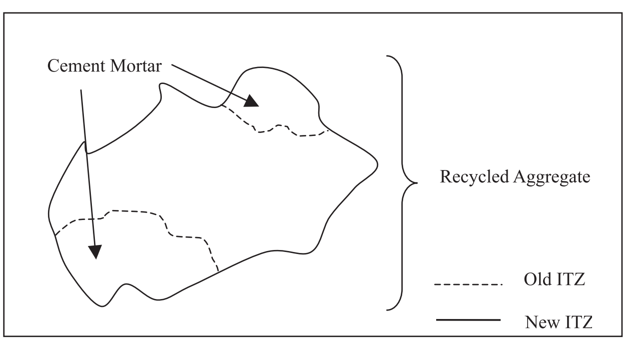


Fig. 6. Interfaces of recycled aggregate.

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 Fig. 7), while similar cracks in RA still remain unfilled for NMA (see Fig. 8). Furthermore, more voids and cracks are found between RA and mortar for NMA (see Figs. 9 and 10) since complete hydration of the mortar at ITZ is hampered due to inadequacy of water. Figs. 11 and 12

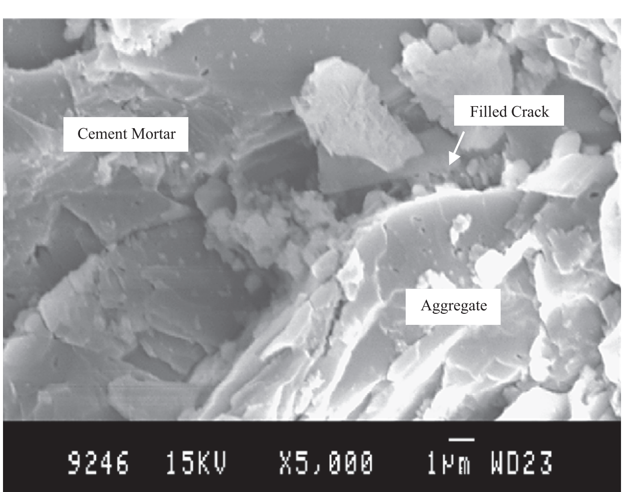


Fig. 7. Filled crack in RA using TSMA.

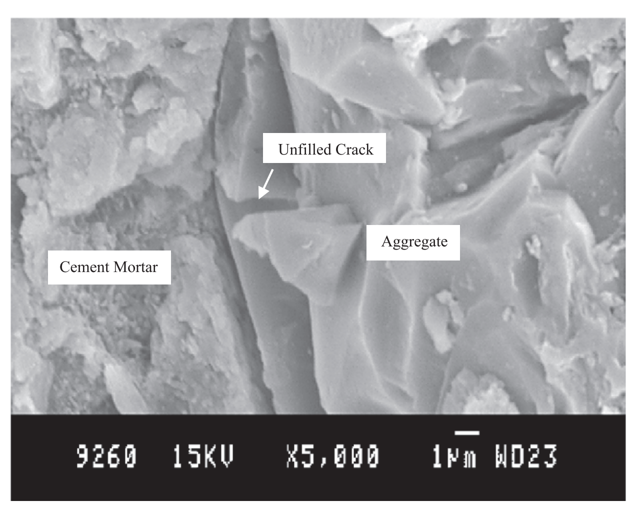


Fig. 8. Unfilled crack in RA using NMA.

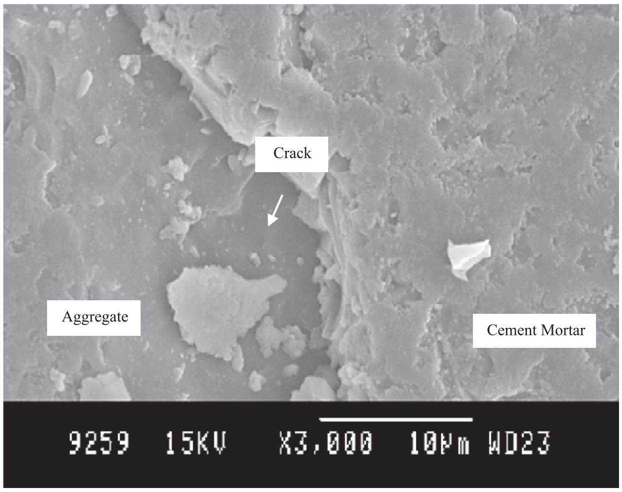


Fig. 9. Crack in RA using NMA.

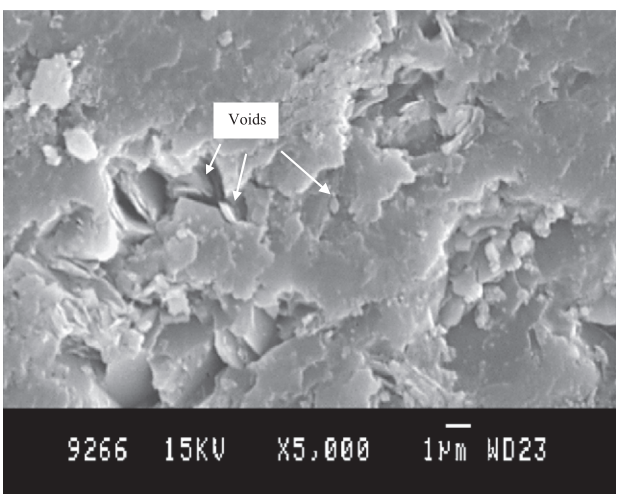


Fig. 10. Voids in RA using NMA.

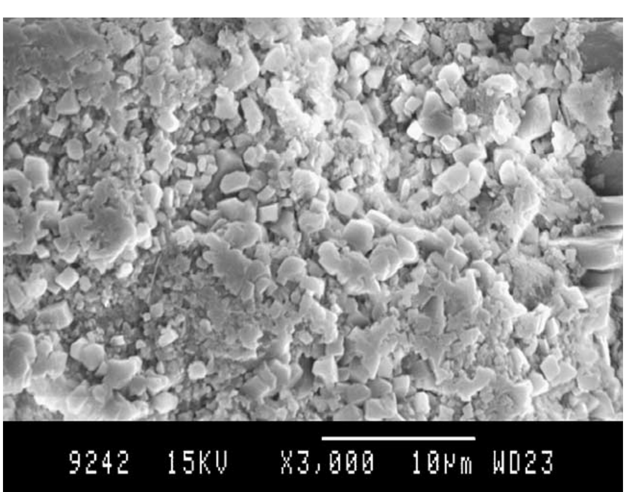


Fig. 11. Dense cement paste for TSMA.

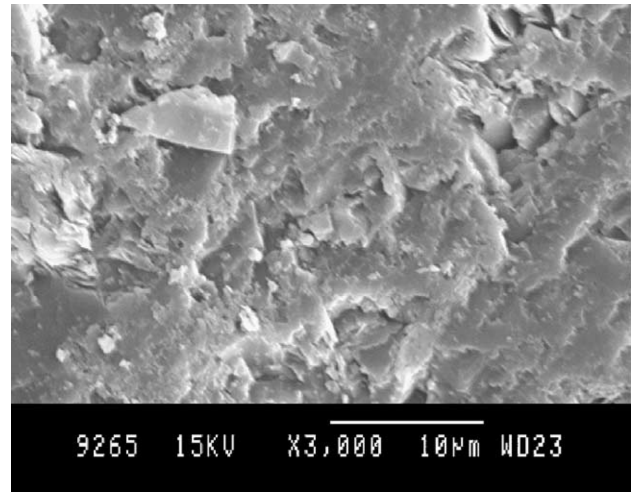


Fig. 12. Loose cement paste for NMA.

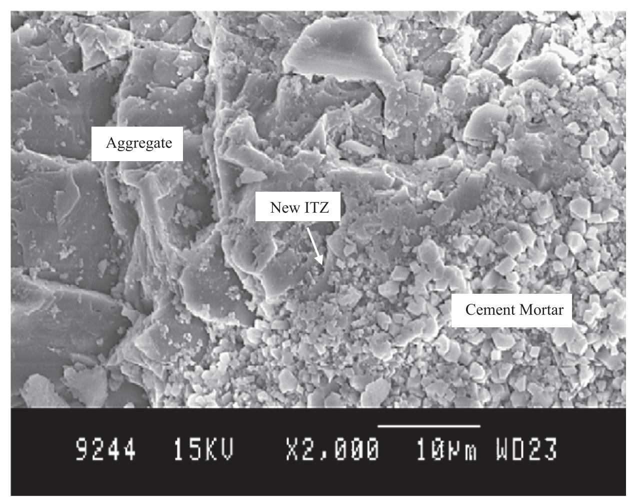


Fig. 13. New interfacial zone for TSMA.

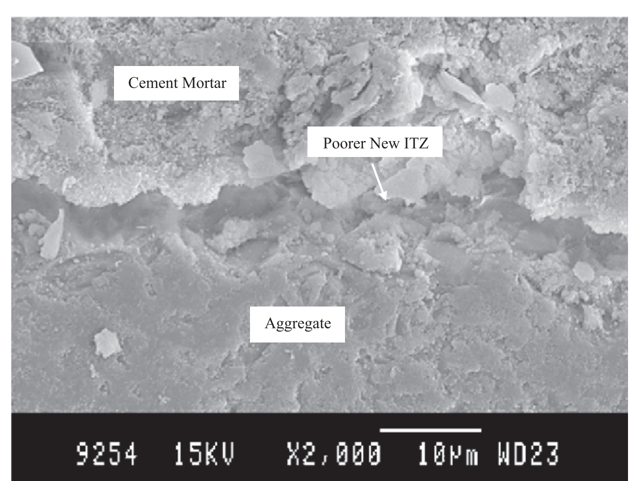


Fig. 14. Poorer new interfacial zone for NMA.

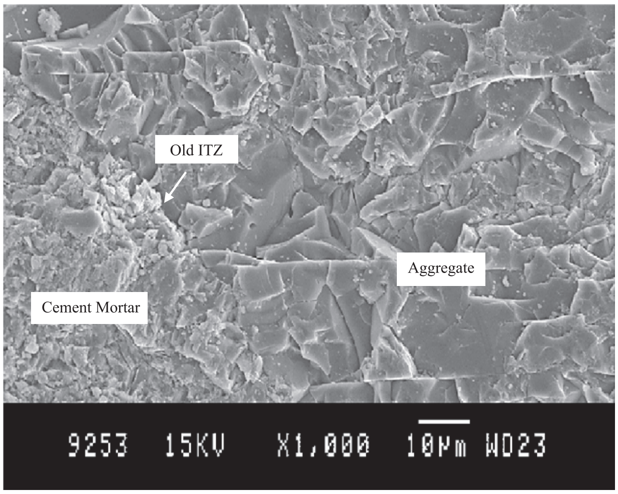


Fig. 15. Old interfacial zone for TSMA.

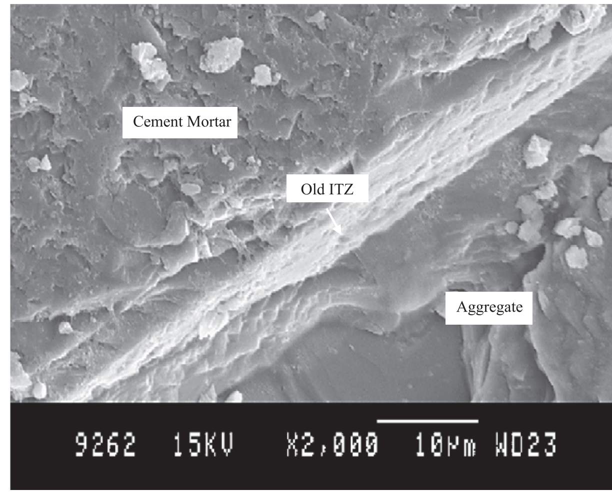


Fig. 17. Old interfacial Zone for NMA.

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. Fig. 13 shows a stronger and denser new interfacial zone in RAC after adopting TSMA compared to the poorer ITZ for NMA, as shown in Fig. 14. Fig. 15 shows a stronger and denser old interfacial zone around RA after adopting TSMA compared to the old ITZ for NMA, as shown in Figs. 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. Fig. 18 illustrates the concrete matrix scenario for TSMA schematically.

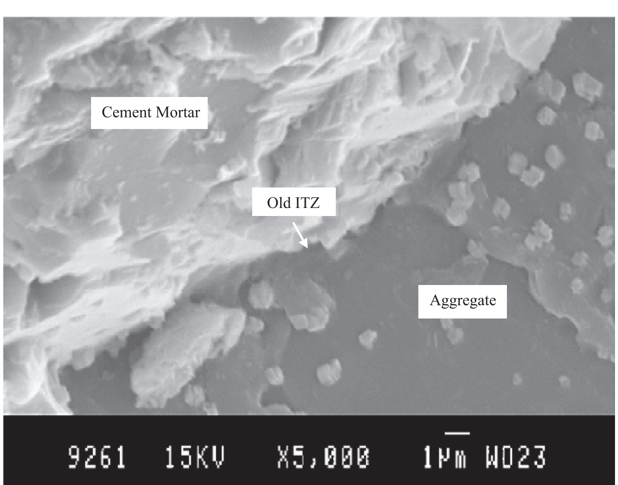


Fig. 16. Old interfacial zone for NMA.

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 strengthen 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.

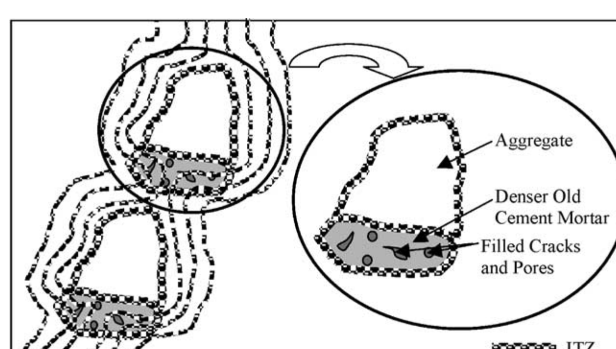


Fig. 18. RA structure after adopting TSMA.

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References

[1] H. Kawano, The state of reuse of demolished concrete in Japan, integrated design and environmental issues in concrete technology, Proceedings of the International Workshop 'Rational Design of Concrete Structures under Severe Conditions': Hakodate, Japan, 7–9 August 1995, E & FN Spon, London, 1995, pp. 243–249.

[2] L.P. Chun, D.E. Scorpio, C.J. Kibert, Strategies for successful construction and demolition waste recycling operations, Journal of Construction Management and Economics 15 (1) (1997) 49–58.

[3] CMRA (Construction Materials Recycling Association), Homepage, available at http://www.cdrecycling.org/ (2003).

[4] EPD (Environmental Protection Department), Homepage, available at http://www.info.gov.hk/epd (2003).

[5] C.F. Hendriks, H.S. Pietersen, Sustainable raw materials: construction and demolition waste, Cachan Cedex, RILEM Publication, France (2000).

[6] R.J. Collins, Reuse of demolition materials in relation to specifications in the UK, Demolition and reuse of concrete and masonry: guidelines for demolition and reuse of concrete and masonry, Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete Masonry, held in Odense, Denmark, 24–27 October 1993, E & FN Spon, London, 1993, pp. 49–56.

[7] CIRIA, Environmental issues in construction: a review of issues and initiatives relevant to construction and related industries, V. 2, Technical Review, Special Publication 94, Construction Industry Research and Information Association, London (1993).

[8] C.F. Hendriks, Certification system for aggregates produced from building waste and demolished buildings, Environmental aspects of construction with waste materials, Proceeding[s] of the International Conference on Environmental Implications of Construction Materials and Technology Developments, Maastricht, the Netherlands, 1–3 June, 1994, pp. 821–834.

[9] M. Mulheron, The recycling of demolition debris: current practice, products and standards in the United Kingdom, Demolition and Reuse of Concrete and Masonry: Reuse of Demolition Waste, Chapman and Hall, London, 1988, pp. 510–519.

[10] M. Torring, Management of concrete demolition waste, Concrete Technology for a Sustainable Development in the 21st century, E & FN Spon, London, 2000, pp. 321–331.

[11] F. Tomosawa, T. Noguchi, New technology for the recycling of concrete—Japanese experience, Concrete Technology for a Sustainable Development in the 21st century, E & FN Spon, London, 2000, pp. 274–287.

[12] T. Nogchi, M. Tamura, Concrete design towards complete recycling, Structural Concrete 2 (3) (2001) 155–167.

[13] R.S. Ravindrarajah, C.T. Tam, Methods of improving the quality of recycled aggregate concrete, Demolition and Reuse of Concrete and Masonry: Reuse of Demolition Waste, Chapman and Hall, London, 1988, pp. 575–584.

[14] M. Kikuchi, T. Mukai, H. Koizumi, Properties of concrete products containing recycled aggregate, Demolition and Reuse of Concrete and Masonry: Reuse Of Demolition Waste, Chapman and Hall, London, 1988, pp. 595–604.

[15] H.K. Cheung, Use of recycled asphalt pavement—a practical approach to asphalt recycling, Materials Science and Technology in Engineering Conference—Now, New and Next 15–17 January 2003.

[16] K.E. Hassan, J.J. Brooks, M. Erdman, The use of reclaimed asphalt pavement aggregates in concrete, waste materials in construction: WASCON 2000, Proceedings of the International Conference on the Science and Engineering of Recycling for Environmental Protection, Harrogate, England, 31 May, 1–2 June 2000, 2000, pp. 121–128.

[17] C.S. Poon, S. Azhar, S.C. Kou, Recycled aggregates for concrete applications, Materials Science and Technology in Engineering Conference—Now, New and Next 15–17 January 2003.

[18] K. Yoda, T. Yoshikane, Y. Nakashima, T. Soshiroda, Recycled cement and recycled concrete in Japan, Demolition and Reuse of Concrete and Masonry: Reuse of Demolition Waste, Chapman and Hall, London, 1988, pp. 527–536.

[19] J.S. Ryu, An experimental study on the effect of recycled aggregate on concrete properties, Magazine of Concrete Research 54 (1) (2003) 7–12.

[20] Hong Kong Government, Construction standard: testing concrete, Hong Kong Government (1990).

[21] BS 812: Part 109. Methods for determination of moisture content. British Standards Institution, London, United Kingdom (1990).

[22] BD (Buildings Department), Homepage, available at http://www.info.gov.hk/bd/english/index.html (2004).

[23] BS 812: Part 116. Methods for determination of compressive strength of concrete cubes, British Standards Institution, London, United Kingdom (1983).

[24] A.K.H. Kwan, Z.M. Wang, H.C. Chan, Mesoscopic study of concrete: II. Nonlinear finite element analysis, Computers and Structures 70 (5) (1999) 545–556.

[25] M.A. Tasdemir, C. Tasdemir, S. Akyuz, A.D. Jefferson, F.D. Lydon, B.I.G. Barr, Evaluation of strains at peak stresses in concrete: a three-phase composite model approach, Cement and Concrete Composites 20 (4) (1998) 301–318.

[26] Z.M. Wang, A.K.H. Kwan, H.C. Chan, Mesoscopic study of concrete: I. Generation of random aggregate structure and finite element mesh, Computers and Structures 70 (5) (1999) 533–544.

[27] D.P. Bentz, E.J. Garboczi, Simulation studies of the effects of mineral admixtures on the cement paste-aggregate interfacial zone, ACI Materials Journal (1991 (September–October)) 518–529.

[28] S. Mindess, J.F. Young, D. Darwin, Concrete, Upper Saddle River, Prentice Hall, New Jersey, 2003.

[29] P.K. Mehta, P.C. Aitcin, Microstructural basis of selection of materials and mix proportions for high strength concrete, High Strength Concrete Second International Symposium, ACI SP-121, 1990, pp. 265–279.

[30] M.G. Alexander, The effects of ageing on the interfacial zone in concrete, Interfacial transition zone in concrete: state-of-the-art report (1996) 150–174.

[31] W. Jia, L. Baoyuan, X. Songshan, W. Zhongwei, Improvement of paste-aggregate interface by adding silica fume, in: Proceedings of the 8th International Congress on the Chemistry of Cement, vol. 3, 1986, pp. 460–465.

[32] W. Keru, Z. Jianhua, The influence of the matrix-aggregate bond on the strength and brittleness of concrete, Bonding in Cementitious Composites, Materials Research Society, vol. 114, 1988, pp. 29–34.

[33] G. Li, H. Xie, G. Xiong, Transition zone studies of new-to-old concrete with different binders, Cement and Concrete Composites 23 (4–5) (2001) 381–387.

[34] S. Popovics, Attempts to improve the bond between cement paste and aggregate, Materials and Structures 20 (115) (1987) 32–38.

[35] W. Xueqan, L. Dongxu, B. Qinghan, G. Liqun, T. Mingshu, Preliminary study of a composite process in concrete manufacture, Cement and Concrete Research 17 (5) (1987) 709–714.