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Removal of Cement Mortar Remains from Recycled Aggregate Using Pre-soaking Approaches

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Abstract

With a rising tide of adoption of recycled aggregate (RA) for construction, investigation on ways to improve the quality of RA has been overwhelming. The adoption of RA brings benefits including savings in the limited landfill spaces and the use of natural resources. However, the poorer quality of RA often limits its utilization to low grade applications such as sub-grade activities, filling materials and low grade concrete. The major reason that affects the quality of RA is the large amount of cement mortar remains on the surface of the aggregate, resulting in higher porosity, water absorption rates and thus a weaker interfacial zone between new cement mortar and aggregates, which weakens the strength and mechanical performance of concrete made from RA. This paper attempts to study three pre-soaking treatment approaches; namely *ReMortar_{HCl}*, *ReMortar_{H₂SO₄}* and *ReMortar_{H₃PO₄}* in reducing the mortar attached to RA. The results show that the behaviour of RA has improved with reduction in water absorption, without simultaneous exceeding the limits of chloride and sulphate compositions after the treatment. This work has also compared the compressive strength, flexural strength and modulus of elasticity of concrete made from the approaches, which shows marked improvements in quality when compared with those using traditional approaches.

Keywords: pre-soaking treatment, recycled aggregate, recycled aggregate concrete, construction

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1. Introduction

Waste management and sustainable construction have recently been strongly advocated in Hong Kong (Shen and Tam, 2002) . The construction industry plays a vital role in meeting the needs of society and enhancing the quality of life (Shen and Tam, 2002); (Tse, 2001). However, the industry should ensure consistency of its activities and products with environmental policies and good environmental practices through reduction of wastes (Environmental Protection Department, 2006). It is clear that this approach needs to be promoted in the near future.

The best way to deal with material wastes is not to create it in the first place (Snook *et al.*, 1995; Gavilan and Bernold, 1994). Table 1 summarizes problems of the current practices and recommended measures for controlling construction pollutions at the management and operational levels. Four management measures are highlighted including: i) policy; ii) training; iii) audit; and iv) feedback. In addition, two operational measures on design and construction stages are also considered.

<Table 1>

To facilitate waste management, encouraging sorting of construction and demolition (C&D) waste in Hong Kong, the Environment, Transport and Works Bureau of the Hong Kong Special Administrative Region (HKSAR) has issued a technical circular (Ref: 15/2003) on “Waste Management on Construction Sites” guiding practices on sorting and separating various types of construction wastes. Meanwhile, the Hong Kong Housing Authority (HKHA) has trial-implemented a program of selective demolition; one of the projects was in the demolition of a school at Lower Ngau Tau Kok Phase 1 Estate. At the same time, the Buildings Department of HKSAR issued a practice note entitled “Use of Recycled Aggregates in Concrete” in February

2003 (Buildings Department, 2005) to encourage the adoption of RA for construction activities. The Civil Engineering Department of HKSAR has commissioned a pilot recycling plant at Tuen Mun Area 38 to supply RA to the public works projects earmarked for such purposes. All these motions have triggered this study: exploring ways to improve the quality of RA for wider applications.

2. Research Significance

This paper aims to achieve the following objectives:

- i) Investigating the current practices of RA in construction;
- ii) Identifying the major problems that weaken the quality of RAC;
- iii) Developing the pre-soaking treatment methods, namely $ReMortar_{HCl}$, $ReMortar_{H_2SO_4}$ and $ReMortar_{H_3PO_4}$, in reducing the amount of mortar attached to RA;
- iv) Experimenting the three pre-soaking treatment methods and assessing the benefits possibly gained; and
- v) Analyzing the micro-structural behaviour of concrete made using these three pre-soaking treatment methods.

3. Recycled Aggregate

Until recently almost all demolished concrete wastes in Hong Kong were deposited in landfill areas which are in short supply. Hence, reducing waste generation is a pressing issue. Concrete is such an essential, mass-produced material like steel and soil, much effort has been made to recycle and conserve them. However, recycling of concrete and other building materials during the building process of new buildings and at the end of the life cycle is very currently inadequately arranged in Hong Kong. Concrete, in fact, can allow repeated recycling, as is the

case for steel and aluminum (Tomosawa and Noguchi, 2000). Since concrete is composed mainly of cementitious materials, and the powders generated during the production of recycled aggregate can also be reprocessed as cement resources, thus permitting repeated recycling in a fully closed system. Although recycling of concrete demolition waste can provide opportunities for saving resources, energy, time, and money, the quality of Recycled Aggregate Concrete (RAC) is often weakened after adopting RA as reported from many previous research (see Table 2) (Howard Humphreys and Partners, 1994, Torring, 2000). Some examples of reusable concrete waste are tabulated as in Table 3.

<Table 2>

<Table 3>

Although reusing RA reduces the consumption of limited resources and thereby saves costs, it also has shortcomings such as weaker interfacial behaviour between aggregate and cement paste, higher portions of cement mortar attached and lower quality (Aitcin and Neville, 1993, Alexander, 1996, Bentz and Garboczi, 1991, Buch *et al.*, 2000, Coventry, 1999, Farran, 1956, Jia *et al.*, 1986, Kawano, 2000, Keru and Jianhua, 1988, Kwan *et al.*, 1999, Li *et al.*, 2001, Lo, 2000, Mehta and Aitcin, 1990, Mitsui *et al.*, 1994, Mohamed and Hansen, 1999, Olorunsogo and Padayachee, 2002, Popovics, 1987, Ravindrarajah and Tam, 1988, Tasdemir *et al.*, 1998, Tomosawa and Noguchi, 2000, Wang *et al.*, 1999, Xueqan *et al.*, 1987). The deformation properties of concrete mixed with secondary aggregate are more than those of concrete mixed with natural gravel. There are two potential solutions to this problem (Hendriks and Pietersen, 2000): i) substitute 100% gravel by using secondary aggregate and increase the structure dimensions by 10%; and ii) substitution 20% natural aggregate by using mixed recycled aggregate, which does not reduce the quality of the concrete, with strength up to 65MPa.

Although there are many construction projects using RAC, those are only limited to lower-grade applications (Cheung, 2003, Hassan *et al.*, 2000, Poon *et al.*, 2003, Reusser, 1994). RAC cannot provide desirable requirements as normal concrete such as poor strength, high quality variation and high deformation (Benboudjema *et al.*, 2005, Bretschneider, 2004, Environmental Protection Department, 2006, Environmental Transport and Works Bureau, 2006, Khatib, 2005, Tam, 2005, Tam *et al.*, 2005, Yang and Han, 2006). Concrete with recycled aggregate with high porosity, less density and high absorption, tend to be worse in strength and in resistance to freezing and thawing than those made out of ordinary aggregate. Therefore, the following recommendations are proposed to popularise the adoption of recycled aggregate:

- (a) The price of RA should be as competitive as virgin aggregate to encourage the use of RA to replace gravel in concrete;
- (b) Recommendations and specifications for RA should be provided in promoting its use. A detailed requirement should be provided; including the percentage of RA adoption, application areas, requirement of aggregate properties and strength design. RA should also be promoted to be the secondary materials in building construction;
- (c) Since the variety of supply sources causes variations of quality, stricter quality control of RA is required. An authorized party should be responsible for controlling RA quality before adopting these materials;
- (d) Other than setting up recycling plants and quality specification or standard, an information network should be established among them (see Figure 1). The network needs to be built up to share the experience in using RA; and

- (e) To classify different types of RA, the following typical criteria are used such as density, water absorption, portion of fine values and content of organic materials. With further studies and research, a standard classification system can be developed.

<Figure 1>

The limited applications of RA are attributable to their poor qualities. To solve the problems of RAC, some techniques need to be developed for improving the quality of RA, such as to minimize the cement portions adhering to recycled aggregate or separate aggregate from cement paste as much as possible to attain the quality comparable to original aggregate (Tomosawa and Noguchi, 2000).

4. Pre-Soaking Treatment Methods

Since aggregates generally occupy seventy to eighty percent of concrete volume, its selection and proportioning should be given careful attention in order to control the quality of the concrete structure. In addition to their use as economical filler, aggregates generally provide concrete with better dimensional stability and wear resistance. In choosing aggregates for particular uses, attention should be given to three general requirements: economy of the mixture, potential strength of the hardened mass and probable durability of the concrete structure.

The major difference between RA and ordinary aggregates is the amount of cement mortar attached on the surface of aggregate. When old concrete is crushed, a certain amount of mortar from the original cement mortar remains attaching to the stone particles in the RA, which forms a weak, porous and cracky layer (Tam, 2005, Tam, et al., 2005). The porosity of cement mortar attached can directly influence the properties of the aggregate (Barra and Vazquez, 1998); for

examples, lower strength, higher water absorption and lower density. Therefore, removing the cement mortar remains is the best method in improving the quality of RA and making it as competitive as the virgin aggregate.

In this study, three pre-soaking treating methods for RA are proposed and compared. The procedure is first to soak the RA in an acidic environment at around 20°C for twenty-four hours and then watering with distill water to remove the acidic solvents afterward. Before concrete mixing, twenty-four hours water soaking of RA is stipulated according to the specifications of the Buildings Department (BD) (Buildings Department, 2005). Three acidic solvents are experimented in this paper, namely hydrochloric acid (HCl), sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4) with concentration of 0.1 mole [if concentrated acid is used, dilute it with distill water with concentration of about 0.1 mole], which are abbreviated as $ReMortar_{HCl}$, $ReMortar_{H_2SO_4}$ and $ReMortar_{H_3PO_4}$ respectively. A concentration of about 0.1 mole chosen for the acidic solution can provide a suitable acidic environment for the aggregate to remove the old cement mortar and will not lower the aggregate quality. The solution can also be used to effectively improve the aggregate quality. Figure 2 illustrates the pre-soaking treatment procedures while Table 4 shows the symbols used.

<Figure 2>

<Table 4>

As the recommended percentage of RA substitution is limited to 30% in Hong Kong, 5%, 10%, 15%, 20%, 25% and 30% of RA have been experimented using $ReMortar_{HCl}$, $ReMortar_{H_2SO_4}$ and $ReMortar_{H_3PO_4}$, with the RA collected from the centralized recycling plant at Tuen Mun Area 38. Gradation curves of Aggregate with 20mm and 10mm are shown in Figure 3 and Figure 4, in

which it shows that the aggregate is within the upper and lower limits of the British standard (BS 882, 1992). The designated mix proportions accord to the specifications of the Buildings Department (BD) (Buildings Department, 2005) with a water to cement ratio of 0.45.

5. Results

5.1 Pre-Soaked Recycled Aggregate

The water absorption (BS 812: Part 2, 1995), chloride content (BS 812: Part 117, 1988), sulphate content and pH values of 10mm and 20mm sized recycled aggregates before and after the three pre-soaking treatment methods are summarized in Table 5.

<Table 5>

5.2 Recycled Aggregate Concrete

After the pre-soaking treatments, concrete specimens made from the treated RA in the forms of 100mm sized cube, 100mm x 500mm beam, and 100mm diameter cylinder according to British Standard and ASTM Standard (ASTM C293-00, 2001, BS 1881: Part 116, 1983, BS 1881: Part 121, 1983) are prepared to assess their compressive strength, flexural strength and static modulus of elasticity. The pH values are also examined. The results are then compared with those made from the normal approach (without any pre-soaking in acidic environment). Each types of experimental work are repeated three times and the average values between them are obtained to reduce the variation between samples and results. The percentages of improvement are recorded and tabulated in Table 6 and Table 7 respectively.

<Table 6>

<Table 7>

6. Discussions

The overall porosity of aggregates depend either upon a consistent degree of particle porosity or represent on the average value for a mixture of variously high and low absorption materials (Hewlett, 1988). Owing to the existence of old cement mortar, the porosity of recycled aggregates is increased. Comparing to natural aggregates, recycled aggregates have higher porosity and thus higher water absorption rates. The water absorption rates for RA are between 3 to 10 percent, compared to less than 1 up to 5 percent for natural aggregates (Building Contractors Society of Japan, 1978); (Hansen and Narud, 1983); (Narud, 1981); (Ravindrarajah and Tam, 1985); (Hasaba *et al.*, 1981). The higher water absorption of the coarse aggregate is resulted from the higher absorption rate of the old cement mortar attached to the aggregate particles (Hansen, 1986); (Kobayashi and Kawano, 1988); (Lamond *et al.*, 2002). This characterizes concrete made with higher water absorption recycled aggregate with reduction in compressive strength and less resistant to freezing and thawing than those with ordinary aggregates (Kobayashi and Kawano, 1988).

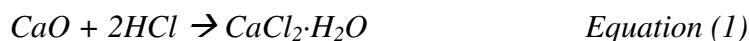
Since the cement mortar attached to the RA is the major factor that weakens the mechanical behaviour of concrete, pre-treating RA is necessary to improve their quality. Table 5 shows that the water absorption rates after the pre-treatments have been significantly reduced with improvements between 7.27% and 12.17%. This shows that the pre-treatments can effectively remove a great portion of old cement mortar from RA, which helps improve the weak link of RA and new cement mortar. Although the chloride and sulphate contents have increased after the pre-treatments, they are still within the limits according to the respective standards of 0.05% and 1% (Buildings Department, 2005). Regarding the pH values, the pre-treated RA using $ReMortar_{HCl}$,

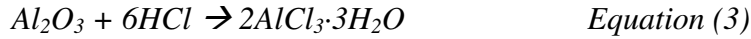
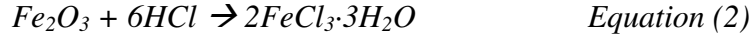
ReMortar_{H₂SO₄} and ReMortar_{H₃PO₄} are still within the alkaline group (above 8.5pH). These show the small adversarial effect to the RA after the acidic pre-treatments.

From the results shown in Table 6, the mechanical properties of recycled aggregate concrete have recorded marked improvements after the pre-treatments. Table 7 shows that 21.84 percent improvement with 20 percent RA substitution is recorded for compressive strength at 7 days curing, 22.90 percent improvement with 25 percent RA substitution recorded for flexural strength at 14 days curing, and 20.48 percent improvement with 30 percent RA substitution for modulus of elasticity when using the ReMortar_{HCl} approach.

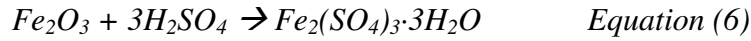
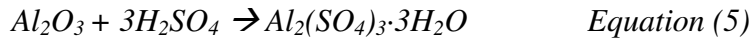
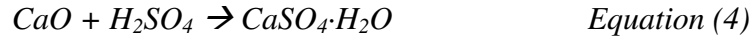
Since the major compositions of cement mortar include calcium oxide (CaO), silicon dioxide (SiO₂), aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃) (see Table 8), the reactions under the acidic environment are described by *Equations (1) to (3)*, *Equations (4) to (6)*, *Equations (7) to (9)* for ReMortar_{HCl}, ReMortar_{H₂SO₄} and ReMortar_{H₃PO₄} respectively. From that, various reaction products can be generated. However, the unstable reaction products of Ca₃(PO₄)₂·3H₂O and CaHPO₄, 2Fe(PO₄)·3H₂O and FeHPO₄ generated from CaO and Fe₂O₃ with H₃PO₄ [see *Equations (7) and (9)*], are unable to clean up the most cement mortar attached and limit the benefits gained from the pre-treatment approach with an optimal strength improvement of 14.01 percent (with 25% RA substitutions at 28 days curing), 18.82 percent (with 5% RA substitutions at 7 days curing) and 10.82 percent (with 30% RA substitutions) for compressive strength, flexural strength and the static modulus of elasticity respectively.

Reactions under ReMortar_{HCl}:

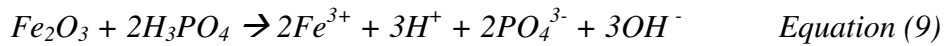
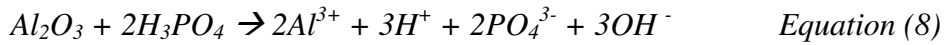




Reactions under ReMortar_{H2SO4}:



Reactions under ReMortar_{H3PO4}:



<Table 8>

In ordinary Portland cement concrete, the interfacial zone between cement paste and aggregate exhibits characteristics significantly different from those of the bulk paste (Aitcin and Neville, 1993); (Bentz *et al.*, 1992); (Mehta and Aitcin, 1990); (Mohamed and Hansen, 1999). The quality of interfacial zone depends on surface characteristics of the aggregate particles, the degree of bleeding, chemical bonding and the specimen preparation technique. As RA has been pre-treated, the interfacial zone behaviour of the aggregate with new cement mortar can be enhanced (Alexander, 1996); (Jia, et al., 1986); (Keru and Jianhua, 1988); (Li, et al., 2001); (Popovics, 1987); (Xueqan, et al., 1987) (see Figure 5:, Figure 6 and Figure 7 for the interfacial zone conditions of ReMortar_{HCl}, ReMortar_{H2SO4} and ReMortar_{H3PO4} respectively) when compared with that of the normal approach (see Figure 8 for the interfacial zone condition). As the paste-aggregate bond strength increases, the concrete strength also increases (Mindess *et al.*, 2003). Thus, the weak link of RA leading to its restrictive low grade applications can be removed.

<Figure 5>

<Figure 6>

<Figure 7>

<Figure 8>

The pre-soaking treatment approach should be considered as cost effective as it can directly remove weak links of recycled aggregate and the old cement mortar attached with at a relatively low cost. The improvement after adopting this method has also been shown by many different types of experimental work. Although it needs investment to implement these pre-soaking approaches, the overall quality for RA is greatly improved and be as competitive as the normal aggregate. In comparing the economic point of view, implementing the pre-soaking approaches costs not more than HK\$500 for treating about 10 tons of recycled aggregate with quality as similar as the normal aggregate. Otherwise, these recycled aggregate can only be dumped to landfills, which is not beneficial to the environment. It should also be noted that concrete waste may also damage the surrounding environment.

7. Conclusions

Using recycled aggregates from demolished concrete wastes has been strongly considered as an effective method for saving the limited landfill spaces and natural resources in Hong Kong. The rare applications of recycled aggregates (RA) for high-grade construction activities are resulted by its poorer and variable quality due to high porosity and water absorption rates. The major reason of this is the cement mortar remains on the surface of RA leading to a porous, highly absorptive and cracky layer during crushing of concrete waste. This paper has studied three pre-soaking treatment methods: $ReMortar_{HCl}$, $ReMortar_{H_2SO_4}$ and $ReMortar_{H_3PO_4}$ aiming at reducing

the old cement mortar attached onto the RA. Experimental results show that the values of water absorption of the pre-treated RA have been significantly reduced with improved mechanical properties for the recycled aggregate concrete. Meanwhile, the alkalinity of recycled aggregate concrete, chloride and sulphate contents of RA have not been adversely affected. Therefore, pre-treating the RA is concluded to be an effective method to improve the quality of RA for higher grade utilization that opens up wider applications of RA for construction activities.

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Table 1: : Problems and Recommended Measures for Controlling Construction Waste by Previous Researchers (Building Research Establishment, 1982, Chan and Ma, 1998, Chan and Li, 2001, Chen *et al.*, 2000, Chen *et al.*, 2002, Coffee, 1999, Construction Industry Review Committee, 2001, Environmental Protection Department, 2006, Gavilan and Bernold, 1994, Lam, 1997, Laufer and Jenkins, 1982, Lingard *et al.*, 2000, Masood *et al.*, 2001, McDonald, 1996, McDonald, 1998, McGrath, 2001, Merchant, 1997, Mills *et al.*, 1999, Nelson, 1994, Poon, 1997, Poon, 2000, Poon *et al.*, 2001, Poon *et al.*, 2001, Rogoff and Williams, 1994, Shen and Tam, 2002, Skoyles and Skoyles, 1987, Snook *et al.*, 1995, Tam *et al.*, 2002, Tam *et al.*, 2004, Tam *et al.*, 2005, Teo and Loosemore, 2001, Warren, 1989, Zeng *et al.*, 2002)

| | Management Level | | | Operational Level | | |
|----------|---|---|--|--|---|---|
| | Policy | Training | Audit | Feedback | Design | Construction |
| Aim | Enhance environmental awareness and company culture | Provide benchmarking measures in understanding the weaknesses | | Achieve continuous improvement | Have an early planning for the environmental issues | Ensure all construction wastage had been minimized by all means |
| Problems | Waste management as a low priority in a project | Insufficient training provided and lack of knowledge on waste minimization technology | Normally no benchmarking tool provided in an organization | No encouragement to provide feedback | Lack of consideration of environmental issues in the design stage | Waste generation is increasing |
| Measures | <ul style="list-style-type: none"> • Set up environmental policy • Demonstrate greater commitment to waste management • Implement waste management plan • Consider reduction of construction waste and awareness of environmental protection as basic requirements in building management | <ul style="list-style-type: none"> • Provide training programme to all levels of employees | <ul style="list-style-type: none"> • Provide benchmarking measures for understanding the problems of the current measure and provide some improvements • Incentive reward scheme | <ul style="list-style-type: none"> • Provide feedback loop from the public and in-house employees • Improve building construction technology by research or adoption | <ul style="list-style-type: none"> • Use long-life construction materials, such as steel • Consider dimensional coordination construction • Minimize variations • Flexible design • Purchasing quantity of materials just required • Consider site selection • Provision of adequate information on maintenance • Clear specification • Use environmental- friendly construction method and modular design, such as prefabrication • Avoid buying poor quality materials • Coordinate with designer and specification writer to use recyclable materials | <ul style="list-style-type: none"> • Reuse, recycle and reduction • Good site planning • Separation of construction materials • Well-organized site and proper storage facilities • Use of secondary materials • Avoid complex and labour intensive works • Labeling of construction materials • Effective logistics • Agreements with subcontractors • Avoid overloading limited storage space on site • Avoid unnecessary handling • Less packaging or reusable packaging • Adopt just-in-time ordering • Avoid damage while unpacking on site • Order appropriate material sizes to minimize cutting, and order appropriate quantities to avoid excess • Designate central areas for cutting and storage so reusable pieces can easily be located • Review waste management periodically to identify additional waste reduction alternatives • Employ competent subcontractors and skill labourers |

Table 2a: Summary on the Previous Researches on RAC

| Source(s) | Replacement ratio | Compressive strength* | Flexural strength* | Modulus of elasticity* |
|---------------------------------|---|-----------------------|------------------------|------------------------|
| (Acker, 1998) | 100% replacement of coarse recycled aggregate (CRA) | 17.2% lower | 20% lower | 23% lower |
| (Ahmed and Struble, 1995) | 100% replacement of CRA | 33% lower | 16% lower (at 14 days) | |
| (Bretschneider, 2004) | 100% replacement of CRA | | 8.1% lower | 11.9% lower |
| | 75% replacement of CRA | | | 4.0% lower |
| | 50% replacement of CRA | | 8.1% lower | 5.8% lower |
| (Frondistou-Yannas, 1977) | 100% replacement of CRA | 4% to 14% lower | | 40% lower |
| (Grubl <i>et al.</i> , 2004) | 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, 1988) | 100% replacement of CRA | 30% lower | | |
| (Ikeda <i>et al.</i> , 1988) | 100% replacement of CRA | 15% to 40% lower | | 30% to 50% lower |
| (Kakizaki <i>et al.</i> , 1988) | 100% replacement of CRA and fine recycled aggregate (FRA) | 32% lower | | 40% lower |

| | | | | |
|--|--------------------------|------------------|-------------|-------------|
| (Masood, et al., 2001) | 10% replacement of FRA | 20% lower | 4.2% lower | 32.4% lower |
| | 20% replacement of FRA | 22.6% lower | 7.3% lower | 22.7% lower |
| | 30% replacement of FRA | 25.5% lower | 10.4% lower | 20.2% lower |
| (Nishibayashi and Yamura, 1988) | 100% replacement of CRA | 15% to 30% lower | | 15% lower |
| (Roos, 2003)] | 100% replacement of CRA | 34% lower | | 36.4% lower |
| (Teranishi <i>et al.</i> , 1998) | 50% replacement of CRA | 57.8% lower | | 30.5% lower |
| (Topcu, 1997) | 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 | | |
| Notes: * Tests are conducted in the curing of 28 days; and | | | | |
| # The quality of these recycled aggregates is poor, with water absorption of 7% in 30 minutes. | | | | |

Table 2b: Summary on the Previous Researches on RAC

| Source(s) | Replacement ratio | Compressive strength* | Flexural strength* | Modulus of elasticity* |
|--|-------------------------|-----------------------|--------------------|------------------------|
| (Yangi <i>et al.</i> , 1993) | 30% replacement of CRA | 0.3% to 11.2% lower | | 0% to 18.7% lower |
| | 50% replacement of CRA | 1.2% to 16.8% lower | | 2.8% to 25.1% lower |
| | 100% replacement of CRA | 4.1% to 19.7% lower | | 1.1% to 25.8% lower |
| Notes: * Tests are conducted in the curing of 28 days; and # The quality of these recycled aggregates is poor, with water absorption of 7% in 30 minutes. | | | | |

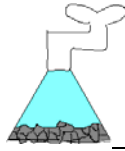
Table 3: Reuse of Demolished Concrete (Kawano, 1995)

| | |
|--------------------------------------|---|
| Demolished Member | Man-made Reef, Paving Stone |
| Broken into 20 to 40cm | Protection of Levee |
| Crushed (-50mm) | Sub-base, Backfilling, Foundation Materials |
| Crushed and Worn (-40mm) | Concrete and Asphalt Concrete Aggregate Sub-Base Material, Backfilling Material |
| Powder (by-product through crushing) | Filler for Asphalt Concrete, Soil Stabilization Materials |

Table 4: Symbols Used for Representing Various Procedures and Materials



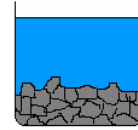
Soaking Aggregate in Acidic Environment



Watering Aggregate with Water



Recycled Aggregate



Soaking Aggregate with Water

Table 5: Properties of Recycled Aggregate before and after Pre-soaking Treatments

| Properties of recycled aggregate | Sizes of aggregate | Before pre-soaking treatment | After pre-soaking treatment | | |
|----------------------------------|--------------------|------------------------------|-----------------------------|---|---|
| | | | ReMortar _{HCl} | ReMortar _{H₂SO₄} | ReMortar _{H₃PO₄} |
| Water absorption (%) | 20mm | 1.65 | 1.45 | 1.48 | 1.53 |
| | 10mm | 2.63 | 2.31 | 2.37 | 2.41 |
| Chloride content (%) | 20mm | 0.0016 | 0.0025 | 0.0001 | 0.0001 |
| | 10mm | 0.0012 | 0.0056 | 0.0001 | 0.0001 |
| Sulphate content (%) | 20mm | 0.0025 | 0.0076 | 0.1090 | 0.0110 |
| | 10mm | 0.0025 | 0.0082 | 0.1040 | 0.0109 |
| Value of pH | 20mm | 10.46 | 9.07 | 8.95 | 8.55 |
| | 10mm | 11.63 | 9.34 | 9.35 | 9.33 |

Table 6: Mechanical Properties and pH Values of Recycled Aggregate Concrete for Normal RA and Pre-soaking Treated RA

| Properties of recycled aggregate concrete | | Normal mixing approach (days of curing) | | | Pre-soaking treatments method (days of curing) | | | | | | | | |
|--|-----|---|-------|-------|--|-------|-------|---|-------|-------|---|-------|-------|
| | | | | | ReMortar _{HCl} | | | ReMortar _{H₂SO₄} | | | ReMortar _{H₃PO₄} | | |
| | | 7 | 14 | 28 | 7 | 14 | 28 | 7 | 14 | 28 | 7 | 14 | 28 |
| Compressive strength (MPa) | 5% | 45.05 | 53.04 | 57.26 | 46.90 | 53.83 | 59.12 | 52.76 | 56.50 | 61.10 | 47.70 | 54.95 | 59.10 |
| | 10% | 50.29 | 54.53 | 58.98 | 50.33 | 54.89 | 59.37 | 51.51 | 58.89 | 60.98 | 54.54 | 57.18 | 60.84 |
| | 15% | 45.14 | 51.72 | 56.26 | 47.31 | 53.73 | 57.59 | 47.82 | 53.62 | 57.93 | 46.97 | 52.32 | 60.67 |
| | 20% | 42.21 | 51.92 | 53.68 | 51.43 | 54.62 | 59.09 | 43.05 | 56.80 | 59.53 | 43.24 | 52.13 | 53.72 |
| | 25% | 51.09 | 52.62 | 52.31 | 51.18 | 53.64 | 55.80 | 51.85 | 53.69 | 59.00 | 51.33 | 54.11 | 59.64 |
| | 30% | 45.49 | 54.58 | 58.07 | 53.00 | 56.28 | 61.07 | 51.49 | 55.87 | 58.84 | 49.40 | 56.16 | 58.80 |
| Flexural strength (MPa) | 5% | 5.10 | 5.81 | 5.98 | 5.73 | 6.27 | 6.24 | 5.70 | 6.17 | 6.14 | 6.06 | 6.55 | 6.19 |
| | 10% | 4.74 | 5.02 | 5.49 | 5.50 | 5.44 | 5.60 | 5.30 | 5.41 | 5.77 | 5.24 | 5.88 | 6.51 |
| | 15% | 4.57 | 5.41 | 6.10 | 5.00 | 5.42 | 6.17 | 5.15 | 5.59 | 6.19 | 5.14 | 5.87 | 6.20 |
| | 20% | 4.98 | 5.26 | 5.64 | 5.25 | 5.83 | 5.71 | 5.08 | 5.52 | 5.74 | 5.15 | 5.67 | 5.90 |
| | 25% | 4.73 | 4.76 | 6.08 | 4.97 | 5.85 | 6.35 | 5.13 | 5.41 | 6.13 | 4.83 | 5.59 | 6.18 |
| | 30% | 4.88 | 4.93 | 6.14 | 5.03 | 5.31 | 6.30 | 5.20 | 5.68 | 6.20 | 5.05 | 5.46 | 6.16 |
| Static modulus of elasticity (N(mm ²) ⁻¹ *) | 5% | 31065 | | | 32830 | | | 32573 | | | 33456 | | |
| | 10% | 29729 | | | 30636 | | | 34298 | | | 31931 | | |
| | 15% | 30279 | | | 31548 | | | 31013 | | | 30668 | | |
| | 20% | 29118 | | | 31253 | | | 31437 | | | 31765 | | |
| | 25% | 29303 | | | 29890 | | | 29320 | | | 31016 | | |
| | 30% | 28194 | | | 33969 | | | 30951 | | | 31245 | | |
| Scale of pH* | 5% | 12.50 | | | 12.61 | | | 12.69 | | | 12.67 | | |
| | 10% | 12.71 | | | 12.59 | | | 12.71 | | | 12.63 | | |
| | 15% | 12.57 | | | 12.55 | | | 12.69 | | | 12.63 | | |
| | 20% | 12.73 | | | 12.65 | | | 12.81 | | | 12.75 | | |
| | 25% | 12.20 | | | 12.68 | | | 12.50 | | | 12.64 | | |
| | 30% | 12.47 | | | 12.81 | | | 12.64 | | | 12.74 | | |

Notes: *The results obtained from recycled aggregate concrete at 28-day curing

Table 7: Improvement on Mechanical Properties of Recycled Aggregate Concrete after Pre-soaking Treatments

| Properties of recycled aggregate concrete | | Pre-soaking treatments method (days of curing) | | | | | | | | |
|--|-----|--|--------|--------|---------------------------|--------|--------|---------------------------|--------|--------|
| | | ReMortar _{HCl} | | | ReMortar _{H2SO4} | | | ReMortar _{H3PO4} | | |
| | | 7 | 14 | 28 | 7 | 14 | 28 | 7 | 14 | 28 |
| | | Improvement when compared with NMA | | | | | | | | |
| Compressive strength (MPa) | 5% | 4.11% | 1.49% | 3.25% | 17.11% | 6.52% | 6.71% | 5.88% | 3.60% | 3.21% |
| | 10% | 0.08% | 0.66% | 0.66% | 2.43% | 8.00% | 3.39% | 8.45% | 4.86% | 3.15% |
| | 15% | 4.81% | 3.89% | 2.36% | 5.94% | 3.67% | 2.97% | 4.05% | 1.16% | 7.84% |
| | 20% | 21.84% | 5.20% | 10.08% | 1.99% | 9.40% | 10.90% | 2.44% | 0.40% | 0.07% |
| | 25% | 0.18% | 1.94% | 6.67% | 1.49% | 2.03% | 12.79% | 0.47% | 2.83% | 14.01% |
| | 30% | 16.51% | 3.11% | 5.17% | 13.19% | 2.36% | 1.33% | 8.60% | 2.89% | 1.26% |
| Flexural strength (MPa) | 5% | 12.35% | 7.92% | 4.35% | 11.76% | 6.20% | 2.68% | 18.82% | 12.74% | 3.51% |
| | 10% | 16.03% | 8.37% | 2.00% | 11.81% | 7.77% | 5.10% | 10.55% | 17.13% | 18.58% |
| | 15% | 9.41% | 0.18% | 1.15% | 12.69% | 3.33% | 1.48% | 12.47% | 8.50% | 1.64% |
| | 20% | 5.42% | 10.84% | 1.24% | 2.01% | 4.94% | 1.77% | 3.41% | 7.79% | 4.61% |
| | 25% | 5.07% | 22.90% | 4.44% | 8.46% | 13.66% | 0.82% | 2.11% | 17.44% | 1.64% |
| | 30% | 3.07% | 7.71% | 2.61% | 6.56% | 15.21% | 0.98% | 3.48% | 10.75% | 0.33% |
| Static modulus of elasticity (N(mm ²) ^{-1*}) | 5% | 5.68% | | | 4.85% | | | 7.70% | | |
| | 10% | 3.05% | | | 15.37% | | | 7.41% | | |
| | 15% | 4.19% | | | 2.42% | | | 1.28% | | |
| | 20% | 7.33% | | | 7.96% | | | 9.09% | | |
| | 25% | 2.00% | | | 0.06% | | | 5.85% | | |
| | 30% | 20.48% | | | 9.78% | | | 10.82% | | |

Table 8: Compositions of Cement (Yangi, et al., 1993)

| Compound | Percentages (%) |
|------------------------------|-----------------|
| Calcium oxide (CaO) | 65.1 |
| Silicon dioxide (SiO_2) | 21.8 |
| Aluminum oxide (Al_2O_3) | 4.2 |
| Iron oxide (Fe_2O_3) | 2.5 |
| Sulfite (SO_3) | 2.4 |
| Potassium oxide (K_2O) | 0.72 |
| Sodium oxide (Na_2O) | 0.13 |
| Others | 3.15 |

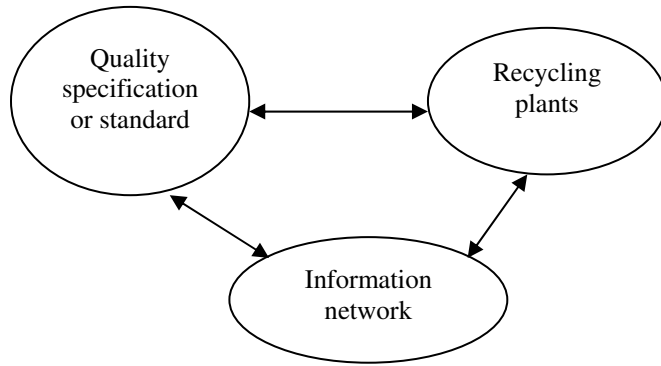


Figure 1: Three Requirements Facilitating Reuse (Kawano, 1995)

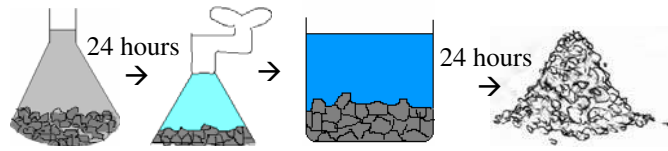


Figure 2: Pre-Soaking Treatment Procedures for Recycled Aggregate

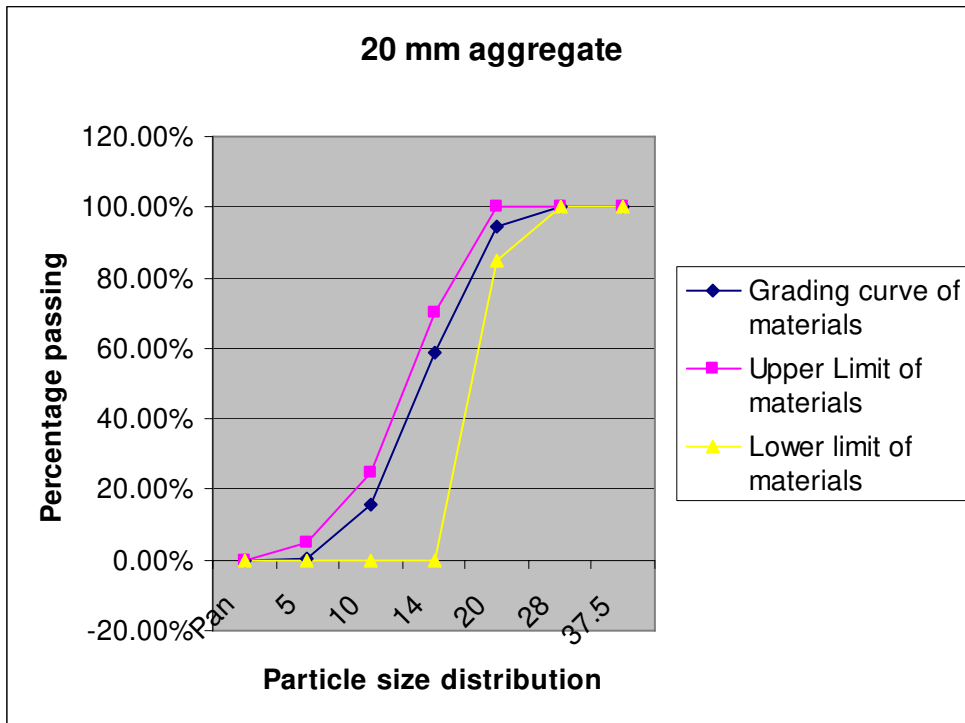


Figure 3: Gradation curve for 20mm recycled aggregate

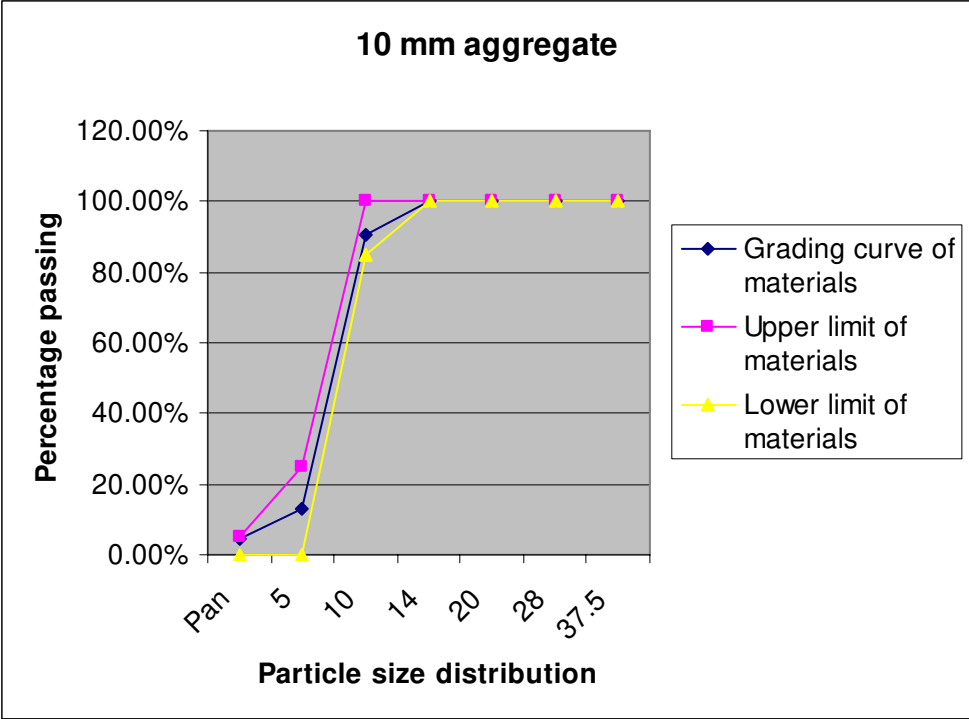


Figure 4: Gradation curve for 10mm recycled aggregate

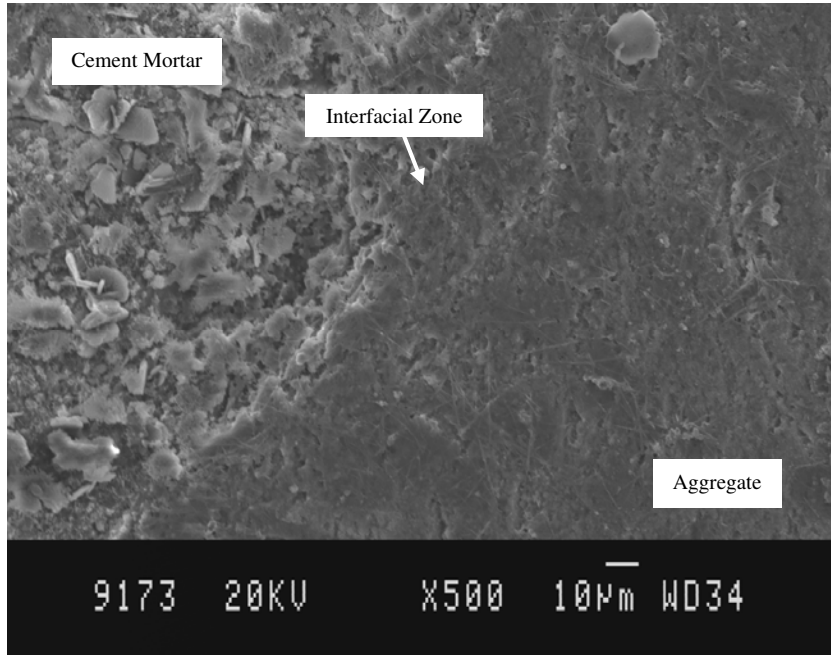


Figure 5: Interfacial Zone for ReMortar_{HCI}

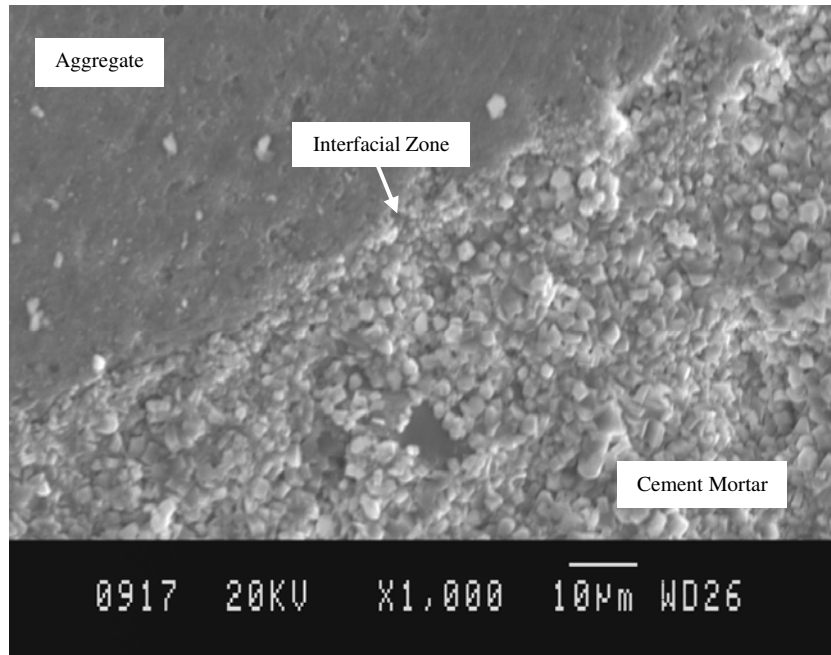


Figure 6: Interfacial Zone for ReMortar_{H2SO4}

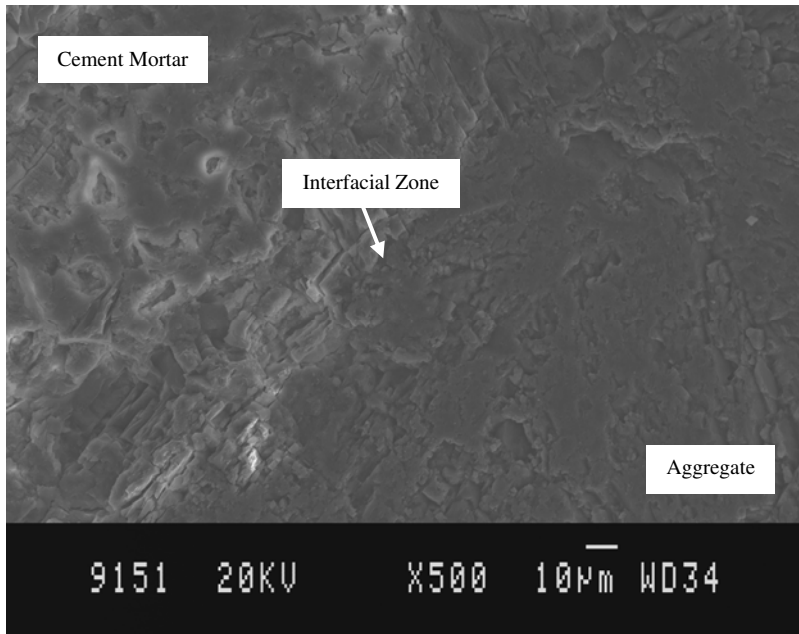


Figure 7: Interfacial Zone for ReMortar_{H3PO4}

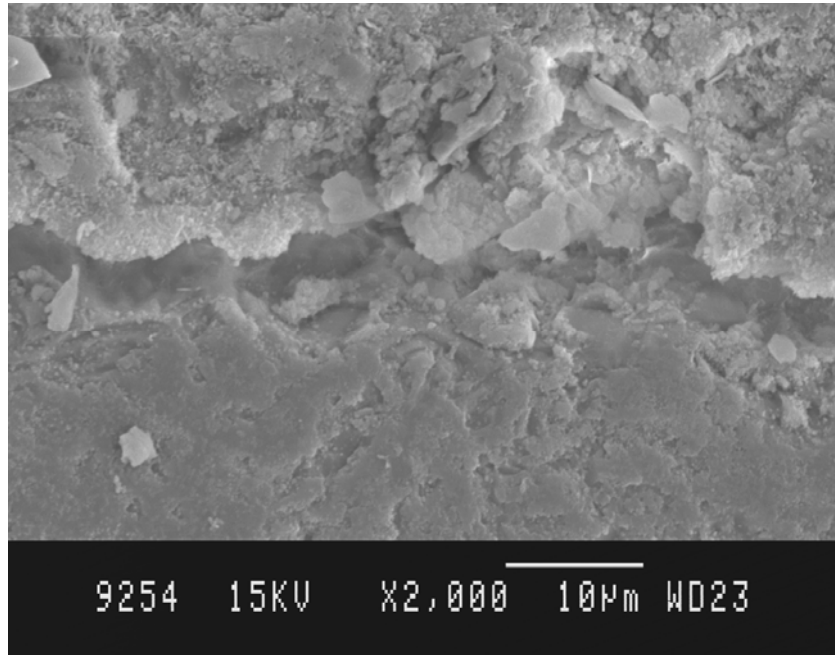


Figure 8: Poorer New Interfacial Zone for Normal Approach (without Pre-soaking Treatments)