Diversifying Two-Stage Mixing Approach (TSMA) for Recycled Aggregate Concrete: TSMA_s and TSMA_{sc}

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Abstract

Recycling demolished concrete as recycled aggregate can be applicable to most construction applications. Lower-grade applications, including sub-base and roadwork, have been practicing in many countries; however, higher-grade activities are rarely discussed. This paper develops two mixing approaches by adding silica fume into certain percentages of Recycled Aggregate (RA) in the pre-mix procedure, named as Two-Stage Mixing $\text{Approach}_{(\text{silica fume})}$ (TSMA_s) and adding silica fume and proportional amounts of cement into certain percentages of RA in the first mix, named as Two-Stage Mixing $\text{Approach}_{(\text{silica fume and cement})}$ (TSMA_{sc}). Experimentation highlights that improvements have been recorded resulted from the use of various RA percentages from both TSMA_s and TSMA_{sc}. The additions of silica fume and proportional cement content in the pre-mix on TSMA_s and TSMA_{sc} can fill up the weak areas in the RA and thus develop a stronger interfacial layer around aggregate, and hence a higher strength of the concrete. It, thus, concludes that TSMA_s and TSMA_{sc} can provide alternative methodologies for further improvement in quality of this recyclable material.

Keywords: Compressive Strength, Two-Stage Mixing Approach, Silica Fume, Cement, Recycled Aggregate Concrete, Waste Management, Construction

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1. Introduction

Promotion of environmental management and sustainable development has been overwhelming in recent years. As a result, there is a growing awareness of environmental issues and the potential problems from deterioration of the environment. Generally speaking, construction is not an environmentally friendly activity. Ofori [1], CIRIA [2], UNCHS [3] and Hill and Bowen [4] provided comprehensive reviews of the effects to the environment from construction activities. These effects include land use and land deterioration, resource depletion, waste generation and various forms of pollution [5-7, 1, 8, 3, 9]. Among various types of construction and demolition (C&D) waste, concrete is found to be the most significant element, with percentages of about 75%, 70%, 40% and 70% collected from construction sites, demolition site, general civil works and renovation works respectively (see Table 1).

<Table 1>

The Hong Kong government has pushed very hard in order to facilitate the recycling of C&D waste, Environment, Transport and Works Bureau of the Hong Kong Special Administrative Region (SAR) issued a technical circular (Ref: 15/2003) on "Waste Management on Construction Sites". Various types of materials are required to be sorted before sending out from construction sites, including all excavated materials, metals, cardboard and paper packaging, plastics, chemical wastes and others. The Housing Authority of the Hong Kong SAR has a trial implementation of selective demolition method in the demolition of a school project at Lower Ngau Tau Kok Phase 1 Estate. Different types of materials are sorted, including timber, steel, florescent tubes, electricity fittings, toilet sets, red bricks, tile, finishes, drainage pipes, cable, in order to improve the recycling rates.

To encourage the adoption of recycled aggregate (RA), Buildings Department of the Hong Kong SAR issued a practice note to authorized persons and registered structured engineers entitled “Use of Recycled Aggregates in Concrete” in February 2003 [10]. The use of RA in concrete is at its initial stage of implementation in Hong Kong. The Civil Engineering Department of the Hong Kong SAR 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. All the recycled aggregates produced need to fulfill the requirements set by the Buildings Department of the Hong Kong SAR.

Although the Hong Kong government has issued guidelines and specifications for construction, the recycling practice is still lagging behind in comparison with other countries. Much of the recyclable materials were dumped as waste. There are many opportunities for the industry to act to improve waste management and recycling [2] to prolong the landfill life, minimize transport needs and reduce the primary resource requirements (mineral and energy). Although there are many material recycling schemes recommended by the Hong Kong government with some practical examples listed in Table 2, actual administering of C&D waste recycling is limited to a few types of solid wastes. When considering a recyclable material, three major areas need to be taken into account [11]: i) economy; ii) compatibility with other materials; and iii) material properties. From a purely economic point of view, recycling of C&D waste is only attractive when the recycled product is as competitive as natural resources in relation to cost and quality. Recycled materials will be more competitive in regions where a shortage of both raw materials and landfilling sites exists.

<Table 2>

A disadvantage of concrete containing a secondary aggregate is that its density is less, and as a result a higher porosity. Hence, more water is needed to ensure full saturation of the aggregate and the concrete may require a more intensive compaction. Although cost saving is minimal in the use of RA, it is nevertheless a useful option for which natural materials might otherwise have to be used. Much of these re-utilized waste are broken materials, which have undergone some form of processing, making them suitable to low-grade applications. However, the modern demolition techniques can generate wastes suitable to produce an end-product product for high-grade applications. At present, only 4% of these waste are sorted, crushed and graded to a standard appropriate for reuse as an alternative to primary aggregate, and they are mainly used for road construction [12].

2. Research Objectives

Under the above context, this paper aims to achieve the following objectives:

i) investigating the concrete waste recycling status in the Hong Kong construction industry;

ii) examining Two-Stage Mixing Approach (TSMA) developed by Tam *et al.* [13] and its benefits;

iii) diversifying the TSMA by additions of silica fume as Two-Stage Mixing Approach$_{\text{(silica fume)}}$ (TSMA$_s$) and Two-Stage Mixing Approach$_{\text{(silica fume and cement)}}$ (TSMA$_{sc}$);

iv) experimenting the TSMA$_s$ and TSMA$_{sc}$ and assessing the benefits possibly gained; and

v) conducting a micro-structural behaviour analysis for TSMA$_s$ and TSMA$_{sc}$.

3. Materials and Methods

3.1 Two-Stage Mixing Approach: TSMA

Two-Stage Mixing Approach (TSMA) was developed by Tam *et al.* [13] for improving the quality of recycled aggregate concrete (RAC), in which it divides the mixing process into two parts and proportionally split the required water into two which are added at different timing; while the normal mixing approach (NMA) only mixes all the ingredients at one go.

Improvement of strength has been recorded up to 21.19 percent for 20 percent of RA used after 28 days of curing for TSMA [13]. 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.

3.2 Two-Stage Mixing Approach$_{(silica\ fume)}$: TSMA$_s$

Silica fume has been accepted as a pozzolanic mineral admixture in concrete. Two-Stage Mixing Approach$_{\text{(silica fume)}}$ (TSMA$_s$) is developed by adding silica fume and replacing two percent of the required cement into certain percentages of RA in the pre-mix procedure. The remaining natural aggregate, fine aggregate, the remaining cement and water are then added during the second mixing process.

3.3 Two-Stage Mixing Approach$_{(silica\ fume\ and\ cement)}$: TSMA$_{sc}$

Another modified mixing approach, namely Two-Stage Mixing Approach$_{\text{(silica fume and cement)}}$ (TSMA$_{sc}$) has been developed. Following similar procedure as used in TSMA$_s$, cement is added proportionally to the percentage of RA used with the addition of silica fume in the pre-mix procedure.

RA from Tuen Mun Area 38 recycling plant is adopted in this study; five to thirty percent of RA have been experimented with the designated mix proportions according to the specifications of Buildings Department of the Hong Kong SAR [10] (see Table 3) and a water to cement ratio of 0.45.

<Table 3>

4. Results

4.1 Compressive Strength

The compressive strengths of the mixes are compared, which is the most important mechanical property of concrete. 100mm sized cubes were made for testing the development of compressive strength 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 [14]. The results of compressive strength and the percentages of improvement in indifferent RA proportions using NMA, $TSMA_s$ and $TSMA_{sc}$ are tabulated in Table 4.

<Table 4>

4.2 Density

The density of hardened concrete is calculated by the mass of a unit volume of hardened concrete expressed in kilograms per cubic metre. 100mm sized cubes were used for testing under the standard curing conditions for 7, 14, 28 and 56 days. Three cubes at different curing periods are experimented and the average was taken. The summary of the experimental results in using NMA, $TSMA_s$ and $TSMA_{sc}$ is tabulated as in Table 5.

<Table 5>

4.3 Flexural Strength

According to ASTM C293-00 [15], flexural strength was investigated by averaging the strengths of three beams in the size of 500mm (length) x 100mm (width) x 100mm (height) under 7, 14, 28 and 56 days curing conditions. Table 6 summarizes the results.

<Table 6>

4.4 Tensile Splitting Strength

For testing the tensile splitting strength in the RAC, averaging the strengths of three 100mm diameter cylinders in 28-day of curing was examined [16]. The summary of the experimental results is tabulated as in Table 7.

<Table 7>

4.5 Static Modulus of Elasticity

For testing the static modulus of elasticity of the RAC, cylinders with 100mm diameter under 28-day curing conditions were examined [17]. Three preloading cycles, using the same loading and unloading rate, were recorded and the average was taken as shown in Table 8.

<Table 8>

5. Discussions

Concrete is of a three-phase system, comprising coarse aggregate, mortar matrix with fine aggregate, and Interfacial Transition Zone (ITZ) between coarse aggregate and the mortar matrix [18-20]. In concrete, ITZ between cement paste and aggregate plays a critical role. At the macroscopic level, concrete is a composite material consisting of discrete aggregate dispersed in a continuous cement-paste matrix [21]. As with other composites, the bond between these two major components of concrete critically determines the mechanical performance.

The weakness of interfacial zone inhibits the achievement of composite action in normal strength concrete [22]. Hence, the interfacial region is generally regarded as the 'weak link' in concrete [23-28]. In fact, the microscopic structure of RAC is much more complicated than that of normal concrete. RAC possesses two ITZs, one between RA and new cement paste (new ITZ), and the other between the aggregate and old mortar attached (old ITZ), which are schematically shown in Figure 1. The cement mortar remains on the RA form the weak link in RAC, which is composed of many minute pores and cracks and they critically affect the ultimate strength of RAC. These pores and cracks increase consumption of water leading to less water for hydration at ITZ for RAC.

<Figure 1>

As RAC cannot achieve the designed requirements as that of normal concrete, the properties of concrete using recycled aggregate will exhibit a higher porosity, less density and higher absorption rate leading to poorer in strength and resistance to freezing and thawing than those made with virgin aggregate [29, 30, 23, 31-34, 24, 25, 18, 26, 22, 35-37, 27, 38-41, 20, 28]. Although there are many records of construction using RAC, they are only limited to lower-grade applications, for examples, pavement, sub-bases and roadwork [42-45].

In order to overcome the these weaknesses of RAC, Two-Stage Mixing Approach (TSMA) developed by Tam *et al.* [13] is modified. The addition of silica fume in the pre-mix procedure is adopted as Two-Stage Mixing Approach$_{\text{(silica fume)}}$ (TSMA$_s$) and an addition of a portion of cement in the first stage of mixing as Two-Stage Mixing Approach$_{\text{(silica fume and cement)}}$ (TSMA$_{sc}$).

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of ferro-silicon and silicon metal. The fume which contains between 85 and 98 percent of silicon dioxide (SiO_2) (see Table 9), and consists of extremely fine spherical glassy particles, is collected by filtering the gases escaping from the furnaces. The average particle size is 0.1μm or about two orders of magnitude finer than cement particles. The specific area is in the order of 20m^2/g measured by the nitrogen absorption method, and the relative density is around 2.2 [46, 47]. Therefore, silica fume is a very fine siliceous material that reacts with the lime liberated during the hydration of Portland cement and forms stable cementitious products [48].

<Table 9>

The effect of silica fume can help in the formation of Calcium Hydroxide [CH or Ca$(OH)_2$] in hydrated paste [49]. It is generally reckoned that the silica fume reacts with CH to accelerate the hydration of Tricalcium Silicate $(3CaO.SiO_2)$ and Dicalcium Silicate $(2CaO.SiO_2)$. A reason for the higher strength of the silica fume paste is due to the pozzolanic nature of silica fume, which also explains why the silica fume pastes become progressively stronger with time [50]. Figure 2 shows the micrography of the crystal distribution from TSMA$_s$ from Scanning Electron Microscopy (SEM).

<Figure 2>

Furthermore, during the pre-mixing process of TSMA$_s$ and TSMA$_{sc}$, silica fume acts as a reinforcing filler for the space inside RA [50-60, 47]; this results in a reduction of size in individual pores and voids within the old cement mortar in RA [53, 54, 61]. These materials change the microstructure of mortars and, consequently, modify some of their properties [62-64, 27, 65, 66].

Addition of silica fume generally results in improved performance of concrete [67, 68, 50, 69, 52, 56, 70, 71, 27, 47]; improvements on strength and rigidity have been recorded for TSMA$_s$ and TSMA$_{sc}$. The greatest improvements on strength and rigidity are recorded at 19.50% (with 25% RA substitution after 28 days), 19.58% (with 25% RA substitution after 56 days), 16.16% (with 10% RA substitution after 28 days) and 16.28% (with 30% RA substitution after 28 days) for TSMA$_s$; and 19.73% (with 25% RA substitution after 28 days), 30.88% (with 25% RA substitution after 14 days), 24.22% (with 5% RA substitution after 28 days) and 11.92% (with 30% RA substitution after 28 days) for TSMA$_{sc}$, on compressive strength, flexural strength, tensile splitting strength and static modulus of elasticity respectively.

In comparison with TSMA$_s$ and TSMA$_{sc}$, improvements on strength and rigidity can be achieved by TSMA$_{sc}$: 10.69% (with 20% RA substitution after 28 days), 12.55% (with 20% RA substation after 14 days), 10.02% (with 5% RA substitution after 28 days) and 6.00% (with 15% RA substitution after 28 days) on compressive strength, flexural strength, tensile splitting strength and static modulus of elasticity respectively. As regards the advantages gained from TSMA$_{sc}$, it can be explained by relatively thick and soft coatings of the silica fume slurry and the necessary cement paste surround RA [50].

Incorporation of silica fume results in a drastic change on the microstructure of the concrete for $TSMA_s$ and $TSMA_{sc}$ [72]. The increase in the strength of mortar and concretes due to the addition of silica fume and portions of cement can be attributed to the improved aggregate-matrix bond associated with the formation of a less porous transition zone and a better interlock between the paste and the aggregate through $TSMA_s$ and $TSMA_{sc}$ [73, 47] on both new ITZ (see Figure 3 and Figure 4 respectively) and old ITZ (see Figure 5 and Figure 6 respectively) in comparison with the traditional mixing approach (see Figure 7 and Figure 8). In $TSMA_{s,}$ silica fume is added, which acts as a reinforcing filler for the space inside RA, resulting in a reduction of size in the individual pores and voids in the old cement mortar for RA. Similar to $TSMA_s$, $TSMA_{sc}$ provides relatively thick and soft coatings of the silica fume slurry and the necessary cement paste surrounding RA in the pre-mix process. Figure 9 illustrates the concrete scenarios for NMA, $TSMA_s$ and $TSMA_{sc}$ schematically. Therefore, $TSMA_s$ and $TSMA_{sc}$ can provide alternative methodologies to improve the quality of RAC.

<Figure 3>

<Figure 4>

<Figure 5>

<Figure 6>

<Figure 7>

< Figure 8>

<Figure 9>

6. Conclusion

As the high tide on recycling C&D waste in Hong Kong, recycling demolished concrete waste as aggregate has been pushed very hard from the Hong Kong government. Setting up concrete recycling plant and issuance of specifications in order to encourage the adoption of recycled aggregate for construction activities have been exercised. However, the poor quality of RAC resulted from the high water absorption, high porosity, weak interfacial behaviour between RA and new cement mortar renders the applications of RAC for higher grade applications difficult. In this study, Two-Stage Mixing Approach$_{\text{(silica fume)}}$ (TSMA$_s$) and Two-Stage Mixing Approach$_{\text{(silica fume and cement)}}$ (TSMA$_{sc}$) are modified from Two-Stage Mixing Approach (TSMA) developed by Tam *et al.* [13] with the addition of silica fume and a portion of cement in the pre-mix process. The use of TSMA$_s$ can develop a denser old cement mortar by filling up the old pores and cracks with silica fume. The TSMA$_{sc}$ is further proposed for enhancing the interfacial behaviour between RA and cement paste, which adopts certain amount of cement and silica fume to gel up the RA, providing a stronger interfacial zone, and thus a higher compressive strength of RAC. From the laboratory testing results, TSMA$_{sc}$ can achieve a higher improvement in comparison with TSMA$_s$. The TSMA$_s$ and TSMA$_{sc}$ can provide an effective methodology for enhancing the strength behaviour of RAC when compared with TSMA. Therefore, TSMA$_s$ and TSMA$_{sc}$ can provide alternative methodologies for further improvement in quality of these recyclable materials.

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Table 1: Composition of Construction and Demolition Wastes Collected in SENT Landfill [26]

Waste Type	Percentage			
	Construction Site	Demolition Site	General Civil Works	Renovation Works
Metal	4%	5%	10%	5%
Wood	5%	7%	0%	5%
Plastic	2%	3%	0%	5%
Paper	2%	2%	0%	1%
Concrete	75%	70%	40%	70%
Rock / Rubble	2%	1%	5%	0%
Sand / Soil	5%	0%	40%	0%
Glass / Tile	3%	2%	0%	10%
Others	2%	10%	5%	4%
Total:	100%	100%	100%	100%

SENT: South East New Territories, HKSAR

Table 2: Recycled Materials for Construction Industry [74]

Recycled Materials	Uses	Local Examples
Aggregates	Sub-base material for road construction, hardcore for foundation works, base / fill for drainage, aggregate for concrete manufacture and general bulk fill	Pilot studies carried out by works department
Asphalt	Aggregate fill and sub-base fill	Under investigation by Highways Department
Excavated Materials	Filling materials	Housing Department's building projects
Public Fill	Land reclamation	Land formation of public filling areas
Pulverized Fuel Ash	Manufacture of concrete products, uses in fill and reclamation, highway construction and reinforced soil structures	Construction of Chek Lap Kok Airport, use in structural concrete for foundation works in the Housing Department's building projects
Metals	Manufacture of new metals	Widely practiced in the local construction industry
Glass	Substitute for sand and aggregates as pipe-bedding material, gravel backfill for walls, crushed stone surfacing, backfill and bedding	Nil
Plastic	Synthetic materials in form of plastic lumber for landscaping, horticulture and hydraulic engineering	Use at some public recreational facilities as garden furniture
Rubber	Manufacture of rubber slate tile use in roofing and sport / playground surface mat	Use at some public recreational facilities as playground surface mat
Expanded Polystyrene	Manufacture of lightweight concrete for non-structural works	Use in manufacturing lightweight concrete in Housing Department's building projects

Table 3: Mix Proportions

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

Table 4: Experimental Results on Compressive Strength

Mixing methods		Compressive strength (MPa)				Improvement when compared with NMA				Improvement when compared with TSMA$_s$			
		7	14	28	56	7	14	28	56	7	14	28	56
NMA	5%	45.05	53.04	57.26	70.27	-				-			
	10%	50.29	54.53	58.98	74.60								
	15%	45.14	51.72	56.26	70.19								
	20%	42.21	51.92	53.68	68.84								
	25%	51.09	52.62	52.31	67.23								
	30%	45.49	54.58	58.07	72.78								
TSMA$_s$	5%	47.93	53.10	58.74	74.60	6.39%	0.11%	2.58%	6.16%	-			
	10%	50.79	54.53	59.26	74.60	0.99%	0.00%	0.47%	0.00%				
	15%	45.47	53.87	60.06	70.53	0.73%	4.16%	6.75%	0.48%				
	20%	47.68	53.47	54.74	69.50	12.96%	2.99%	1.97%	0.96%				
	25%	55.82	60.37	62.51	67.54	9.26%	14.73%	19.50%	0.46%				
	30%	51.15	56.43	61.84	73.55	12.44%	3.39%	6.49%	1.06%				
TSMA$_{sc}$	5%	48.01	53.44	58.81	74.81	6.57%	0.75%	2.71%	6.46%	0.17%	0.64%	0.12%	0.28%
	10%	51.28	55.52	62.83	74.62	1.97%	1.82%	6.53%	0.03%	0.96%	1.82%	6.02%	0.03%
	15%	45.52	53.87	60.33	70.94	0.84%	4.16%	7.23%	1.07%	0.11%	0.00%	0.45%	0.58%
	20%	49.67	54.09	60.59	71.66	17.67%	4.18%	12.87%	4.10%	4.17%	1.16%	10.69%	3.11%
	25%	56.21	61.46	62.63	67.71	10.02%	16.80%	19.73%	0.71%	0.70%	1.81%	0.19%	0.25%
	30%	52.09	56.89	61.85	74.22	14.51%	4.23%	6.51%	1.98%	1.84%	0.82%	0.02%	0.91%

Table 5: Experimental Results on Density

Mixing methods		Density (kg/m^3)			
		7	14	28	56
NMA	5%	2359	2356	2379	2347
	10%	2383	2363	2361	2381
	15%	2363	2377	2342	2347
	20%	2333	2352	2359	2342
	25%	2374	2369	2381	2341
	30%	2366	2360	2381	2352
TSMA$_s$	5%	2376	2357	2376	2370
	10%	2371	2368	2350	2359
	15%	2366	2378	2374	2373
	20%	2377	2365	2355	2360
	25%	2400	2393	2407	2385
	30%	2366	2370	2372	2354
TSMA$_{sc}$	5%	2411	2400	2406	2384
	10%	2395	2391	2395	2377
	15%	2378	2386	2396	2376
	20%	2377	2389	2382	2369
	25%	2363	2385	2381	2338
	30%	2358	2361	2371	2354

Table 6: Experimental Results on Flexural Strength

Mixing methods		Flexural strength (MPa)				Improvement when compared with NMA			
		7	14	28	56	7	14	28	56
NMA	5%	5.10	5.81	5.98	6.28	-			
	10%	4.74	5.02	5.49	5.64				
	15%	4.57	5.41	6.10	6.02				
	20%	4.98	5.26	5.64	6.09				
	25%	4.73	4.76	6.08	6.23				
	30%	4.88	4.93	6.14	6.18				
TSMA_s	5%	5.76	6.20	6.06	7.05	12.94%	6.71%	1.34%	12.26%
	10%	5.65	5.81	5.82	6.20	19.20%	15.74%	6.01%	9.93%
	15%	5.24	6.07	6.26	6.18	14.66%	12.20%	2.62%	2.66%
	20%	5.74	5.92	6.77	6.35	15.26%	12.55%	20.04%	4.27%
	25%	5.62	6.23	6.59	6.66	18.82%	30.88%	8.39%	6.90%
	30%	5.34	5.26	6.20	6.56	9.43%	6.69%	0.98%	6.15%
TSMA_{sc}	5%	5.73	6.27	6.24	6.51	12.35%	7.92%	4.35%	3.66%
	10%	5.50	5.44	5.60	6.31	16.03%	8.37%	2.00%	11.88%
	15%	5.00	5.42	6.17	6.42	9.41%	0.18%	1.15%	6.64%
	20%	5.25	5.83	5.71	6.13	5.42%	10.84%	1.24%	0.66%
	25%	4.97	5.85	6.35	6.23	5.07%	22.90%	4.44%	0.00%
	30%	5.03	5.31	6.30	6.23	3.07%	7.71%	2.61%	0.81%

Table 7: Experimental Results on Tensile Splitting Strength

Mixing methods		Tensile splitting strength (N/m^2)	Improvement when compared with NMA
NMA	5%	3.71	-
	10%	3.57	
	15%	3.65	
	20%	3.81	
	25%	3.66	
	30%	3.59	
$TSMA_s$	5%	4.19	13.02%
	10%	4.14	16.16%
	15%	3.99	9.28%
	20%	4.13	8.53%
	25%	4.13	12.93%
	30%	3.66	1.88%
$TSMA_{sc}$	5%	4.61	24.22%
	10%	4.27	19.64%
	15%	4.04	10.53%
	20%	3.97	4.29%
	25%	4.41	20.49%
	30%	3.79	5.62%

Table 8: Experimental Results on Static Modulus of Elasticity

Mixing methods		Static modulus of elasticity (N(mm^2)$^{-1}$	Improvement when compared with NMA
NMA	5%	31065	-
	10%	29729	
	15%	30279	
	20%	29118	
	25%	29303	
	30%	28194	
TSMA$_s$	5%	31690	2.01%
	10%	30563	2.81%
	15%	30356	0.25%
	20%	29129	0.04%
	25%	29304	0.00%
	30%	32784	16.28%
TSMA$_{sc}$	5%	31144	0.25%
	10%	30867	3.83%
	15%	32176	6.27%
	20%	29137	0.07%
	25%	29306	0.01%
	30%	31556	11.92%

Table 9: Chemical Analysis of Silica Fume [75]

Chemical Analysis	Percentage (%)
Silicon Dioxide (SiO_2)	93.71
Aluminum Oxide (Al_2O_3)	0.21
Ferric Oxide (Fe_2O_3)	0.31
Calcium Oxide (CaO)	0.35
Magnesium Oxide (MgO)	0.47
Sodium Oxide (Na_2O)	0.19
Potassium Oxide (K_2O)	1.19
Phosphorous Oxide (P_2O_5)	0.14
Titanium Oxide (TiO_2)	0.01
Sulphur Trioxide (SO_3)	0.29
Loss on Ignition	2.72
Others	0.41

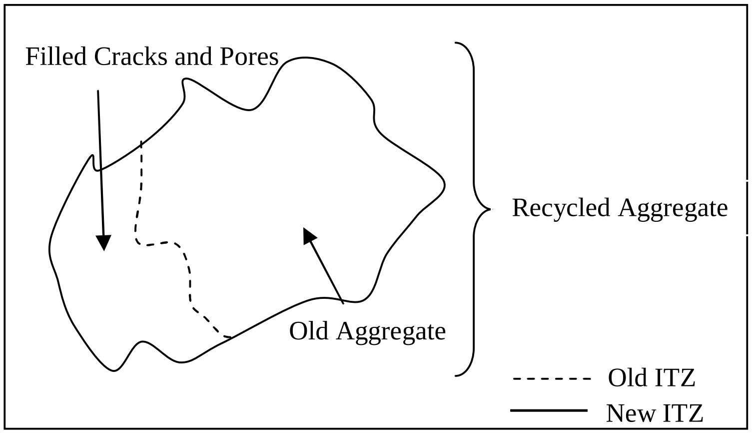

Figure 1: Interfaces of Recycled Aggregate

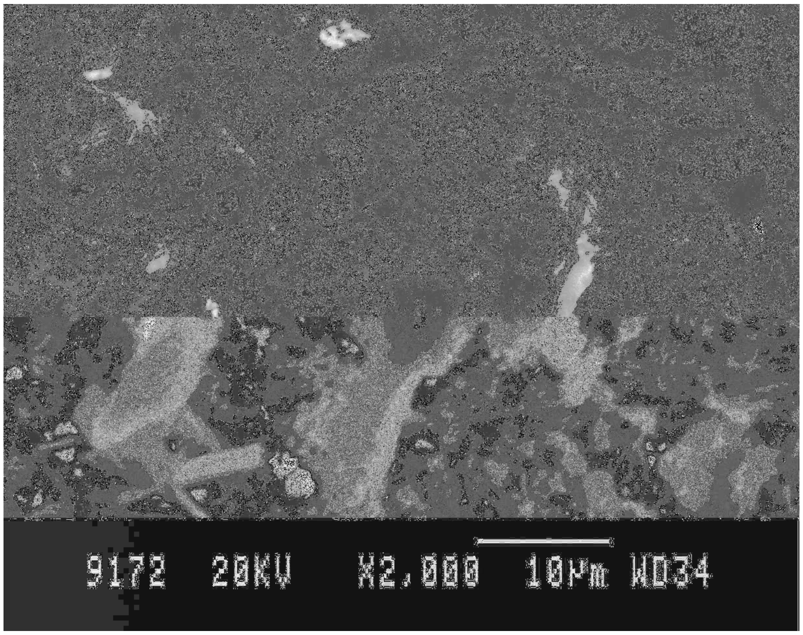

Figure 2: Crystal distribution from $TSMA_s$

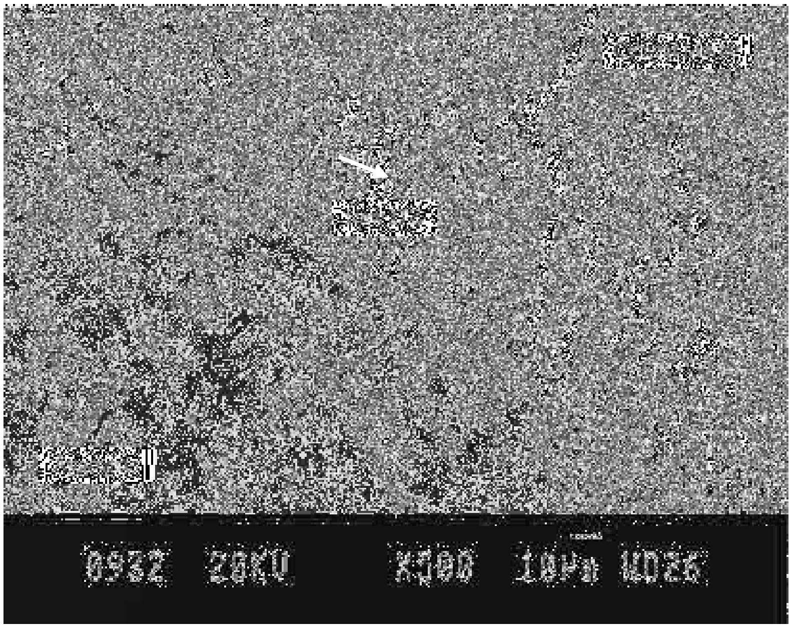

Figure 3: New Interfacial Zone for $TSMA_s$

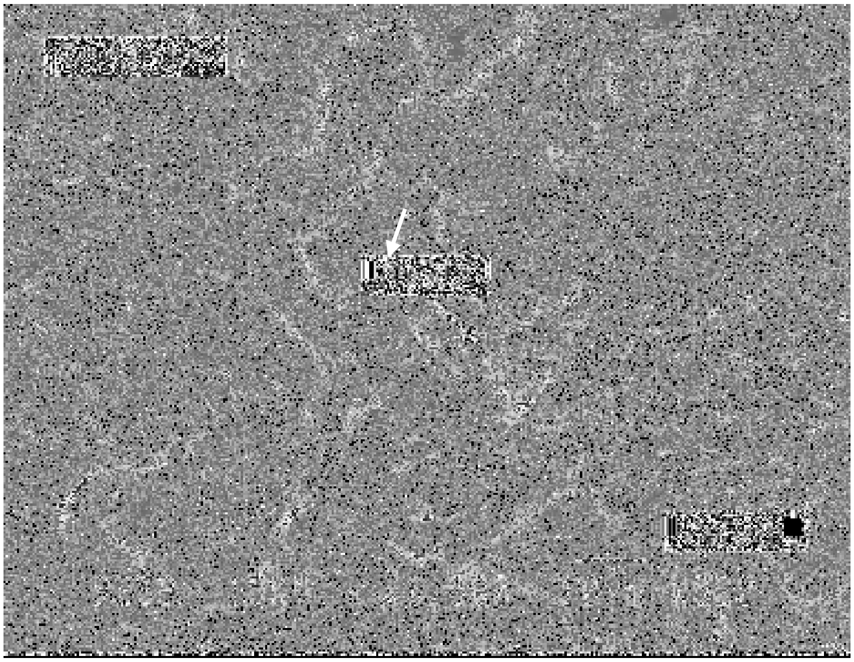

Figure 4: New Interfacial Zone for TSMA$_{sc}$

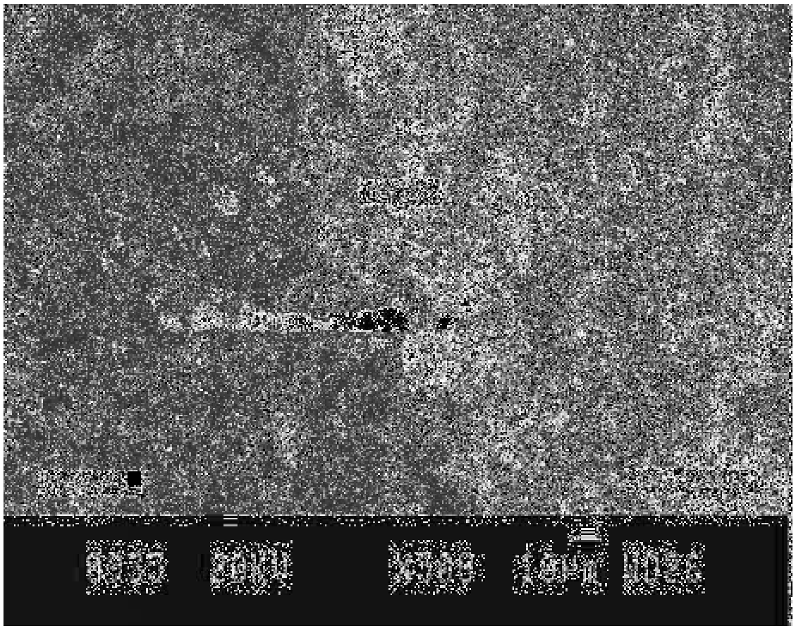

Figure 5: Old Interfacial Zone for TSMA$_s$

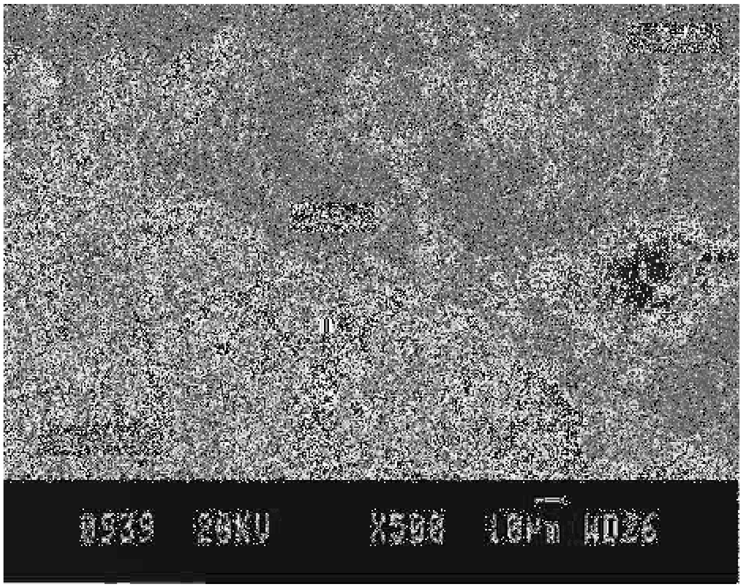

Figure 6: Old Interfacial Zone for $TSMA_{sc}$

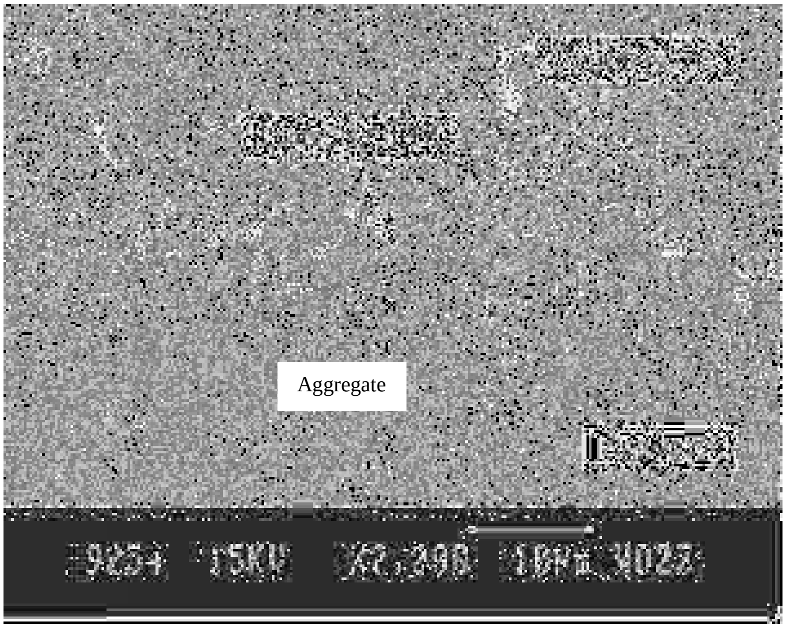

Figure 7: Poorer New Interfacial Zone for NMA

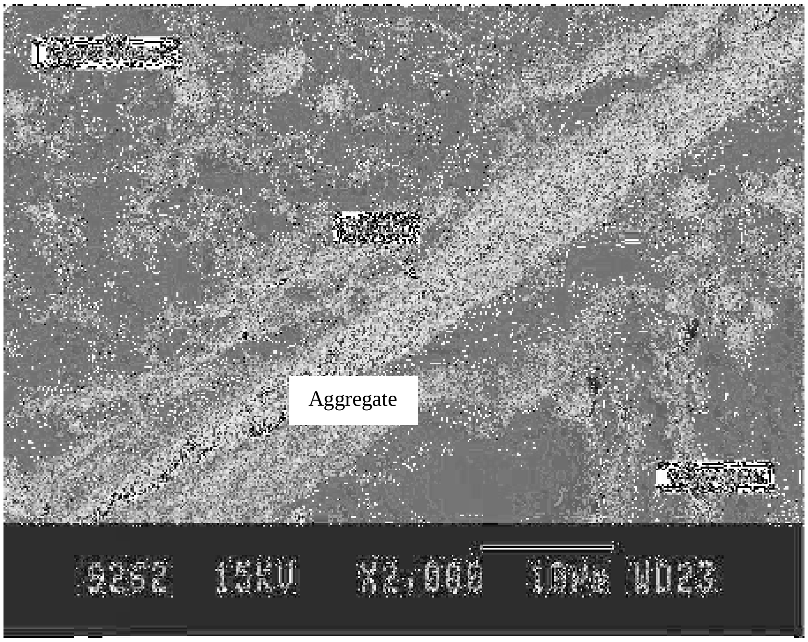

Figure 8: Poorer Old Interfacial Zone for NMA

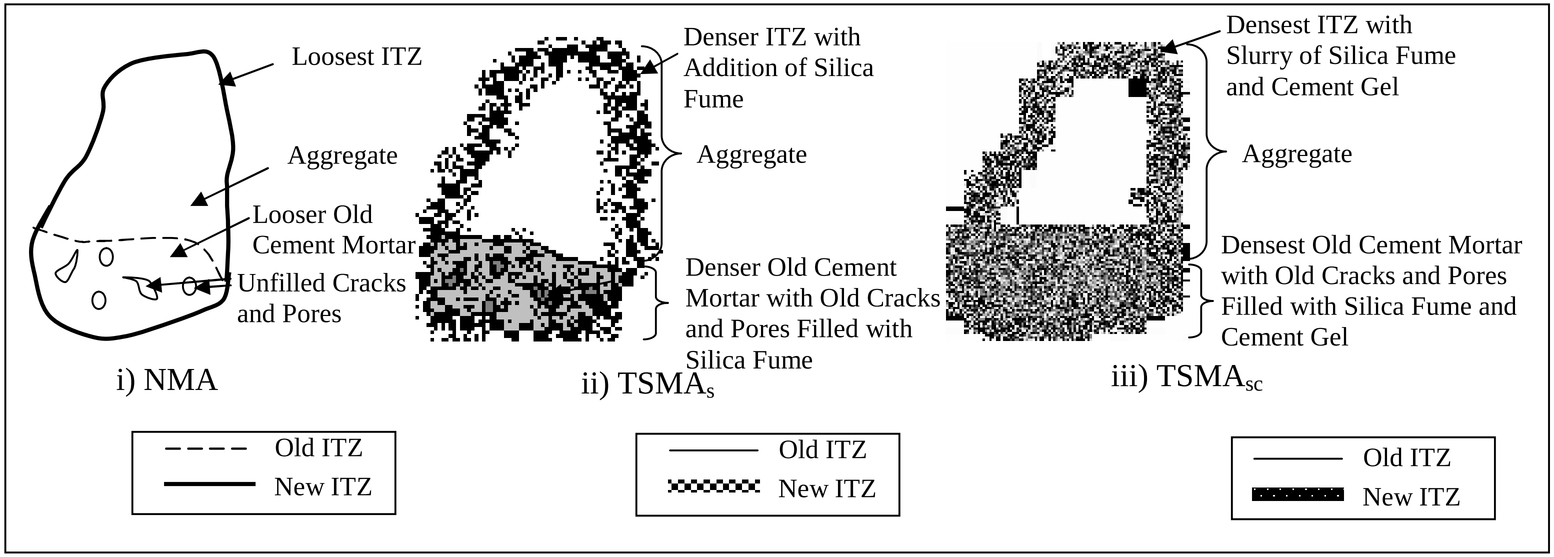

Figure 9: RA Structure after Adopting i) NMA, ii) TSMA$_s$ and iii) TSMA$_{sc}$