Assessment of Durability of Recycled Aggregate Concrete Produced by Two-Stage Mixing Approach

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Abstract

As more than 50% construction and demolition (C&D) wastes are composed of concrete debris in Hong Kong, recycling this debris into Recycled Aggregate (RA) for production of Recycled Aggregate Concrete (RAC) is an efficient way to alleviate the burden on landfill areas. Since RA is generated from concrete debris which has undergone years of services, the resulting RAC bears the weaknesses of lower density, higher water absorption, and higher porosity that limit them to lower-grade applications. Pinpointing to these weaknesses, Tam *et al.* [1] developed the Two-Stage Mixing Approach (TSMA) for improving the strength of RAC, leading to the possibility in applying RAC for higher-grade applications. While the improvement in strength by TSMA has been proven in Tam *et al.'s* work [1], the durability, in terms of deformation (shrinkage and creep) and permeability (water, air and chloride permeability), remains to be verified. In this paper, 0%, 20% and 100% of RA substitutions have been experimented to compare the durability performance of the Normal Mixing Approach (NMA) and the TSMA. Experiment results highlight that: i) the higher the substitutions of RA, the weaker the performance of RAC; and ii) the deformation and permeability of RAC can be enhanced when adopting TSMA. Therefore, it demonstrates that TSMA can help to improve the durability of RAC, on top of the previously verified strength improvement, and thus opening up wider applications of RAC.

Keywords: Deformation, permeability, shrinkage, creep, recycled aggregate concrete.

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1. Introduction

In recent years, recycling of concrete wastes in producing Recycled Aggregate (RA) has been proven to be commercially viable and technically sound for non-structural applications [2] [3] [4] [5]. Such recycling operations can reduce landfill consumption, while conserving primary resources and reducing transport costs [5] [6]. Some of the examples are shown in Table 1 [7].

<Table 1>

Although the reuse of demolished concrete waste can benefit the environment, literature reports show that the cement mortar attached to the recycled aggregate particles creates numerical problems that have confined the application of Recycled Aggregate Concrete (RAC) [2] [5] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32]. This residual mortar alters the absorption and density of aggregate, leading to adverse effects on concrete performance.

The worry on the use of RAC is not limited to structural stability, but also their durability in designing concrete structures [24] [33] [34] [35] [36] [37] [38]. Durability plays an important role in the life cycle cost of a structure; for example, in Japan, it is estimated that the maintenance and renovation costs for infrastructure will exceed 70% of the total public investment in 2010. In the United States, it is estimated that the necessary repairs and improvements to the infrastructure will amount to $3.3 trillion over a period of 19 years. Thus, durability has become a matter of social importance.

To improve the quality of RAC, a new mixing method: Two-Stage Mixing Approach (TSMA) has been developed by Tam *et al.* [1]. The improvement is achieved by forming a layer of cement slurry on the surface of RA to fill up the cracks and voids, leading to an improved interfacial zone at the pre-mix stage. The improvement of strength on TSMA has been proven by Tam *et al.* [1] while the performance on durability remains to be studied. The factors affecting concrete structures' durability have been reported by many researchers. Most agree that deformation (in the forms of shrinkage and creep) and permeability (in the forms of water, air and chloride permeability) are good and reliable indicators to assess the long-term durability of concrete [24] [33] [34] [35] [36] [37] [38].

This paper aims in: i) exploring the Two-Stage Mixing Approach (TSMA) developed by Tam *et al.* [1] by highlighting the improvements to RAC; and ii) experimenting the durability performance of RAC in terms of deformation (in the forms of shrinkage and creep) and permeability (in the forms of water, air and chloride permeability) so achieved by TSMA.

2. Experimental Work

2.1 Methods and Material

In investigating the behaviour of RAC, RA was collected from the centralized recycling plant at Tuen Mun Area 38, which has met the specification of the Buildings Department (BD) of the Hong Kong Special Administrative Region (SAR) [39]. In producing RAC, RA is required to be thoroughly wetted before use and follow the designated mix proportions (see Table 2) with a water to cement ratio of 0.45. The ratio of ordinary Portland cement: fine aggregate: 20mm coarse aggregate: 10mm coarse aggregate: water is 1: 1.8: 1.8: 0.9: 0.45. As the Hong Kong government recommends a limit of 20% RA substitution [24] [40] [41], 0%, 20%, and 100% of RA substitutions have been experimented using the Two-Stage Mixing Approach (TSMA) in comparison with those made with the Normal Mixing Approach (NMA).

<Table 2>

For NMA, the mixer is first 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 [42]. In contrast, TSMA divides the mixing process into two parts and proportionally splits the required water into two which are added at different times. Figure 1 illustrates TSMA mixing procedures.

<Figure 1>

From the study of Tam *et al.* [1], improvements in strength can be achieved up to 21.19% for TSMA (with 20% RA replacement after 28-day of curing). 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. As a result, improvements in strength have been recorded in the works of Tam *et al.* [1]. However, the lack of data on durability hinders the large-scale adoption of this economic and environmentally friendly mixing approach. Therefore, the long-term performance still needs to be examined.

A review of the literature unveils that there are limited studies on the durability of RAC. Drying of concrete occurs in a non-homogeneous manner leading to a strong structural effect; self-equilibrated stresses do arise within the material [43]. The intrinsic behaviour of the deformation of concrete can therefore be deduced in a sort of inverse analysis by focusing on the conventional components: drying shrinkage and creep. Furthermore, the permeability in concrete is a material characteristic bearing a significant influence on concrete durability, specifically regarding freeze-thaw resistance, resistance to chemical attack, and alkaliaggregate reactions [44]. They are considered the important indicators of concrete quality. Table 3 summarizes the standard methods used in testing the performance of RAC.

<Table 3>

2.2 Experimental Results

Although the use of RAC is an effective method in reducing the problems of C&D waste, the problems associated with the quality of RAC are of grave concern. The most important factor influencing the quality is the high water absorption due to the large amounts of old cement mortar attached to the RA. The use of RAC generally leads to about 10% reduction in the compressive and tensile strength, up to 35% reduction in modulus of elasticity, nearly 100% increase in drying shrinkage and 100% increase in the permeability [26] [41]. As a result, the durability of RAC is lower than that of normal concrete [45]. The physical and mechanical properties, durability and deformation become worse when increasing the RA replacement ratio.

2.2.1 Deformation

Deformation is measured by two tests: shrinkage and creep. A saturated cement paste will not remain dimensionally stable when exposed to ambient humidity that is below saturation. This is mainly because of the loss of physically absorbed water from Calcium Silicate Hydrate [$CaO.SiO_2.H_2O$ or *CSH*] [46] [47] [48] [49], resulting in a shrinkage strain. Similarly, when a hydrated cement paste is subjected to a sustained stress, depending on the magnitude and duration of applied stress, *CSH* will lose a large amount of the physically absorbed water and the paste will show a creep strain.

The time-dependent properties of concrete have been researched since the early decades of the last century [50]. Deformation is a complex phenomenon which is influenced by many factors including the constituents, the temperature and relative humidity of the environment, the age when the concrete is subjected to the drying environment and the size of the structure or member [3] [46] [47] [48] [51] [52] [53]. Factors affecting deformation are summarized in Table 4.

<Table 4>

As regards shrinkage of concrete specimens, Table 5 summarizes the average results of the six tests with the change of deformation behaviour shown in Figure 2. Similarly for creep, Table 6 summarizes the average results of the four tests with the change of deformation behaviour shown in Figures 3.

<Table 5>

<Table 6>

<Figure 2>

<Figure 3>

Porosity of aggregate can influence the deformation of concrete samples [49]. Therefore, RA usually leads to higher shrinkage and creep, mainly because the aggregate provides less restraint to the potential deformation of cement paste [3] [5] [54] [55] [56]. Experimentation highlights the increases in shrinkage, creep strain and creep coefficient at 0.131%, 0.001517 and 15.1667 with 100% RA substitution and 0.121%, 0.000563 and 5.633 with 0% RA substitution respectively for NMA after 182 days of curing. The creep rate [*F(K)*] listed in Table 7 shows that a higher substitution of RA will accelerate the creep deformation. For example, 0.00005 strain/day can be recorded on 100% RA substitution and 0.00002 strain/day can be recorded on 0% RA substitution for NMA. However, the difference between 0% and 20% of RA substitutions is not significant.

<Table 7>

Although there is an increase in deformation after the adoption of RA, TSMA helps reduce its impact. From the experimental results, the reduction on creep strain for TSMA is proven; for example, 0.001176 is measured for TSMA and 0.001517 is measured for NMA with 100% RA substitution after 182 days of curing. Creep coefficients obtained give similar results at 11.7611 for TSMA and 15.1667 for NMA with 100% RA substitution after 182 days of curing. An improvement of creep rate [*F(K)*] is recorded with 20% RA substitution at 0.00002 strain/day for TSMA and 0.00003 strain/day for NMA. However, under the controlled humidity condition, the performance in shrinkage did not provide any significant difference between the traditional process and TSMA with the same RA substitution. Furthermore, the deformation of RAC can be improved after adopting TSMA by up to 68.09% in shrinkage and 46.42% in creep (as in the case of 100% RA substitution after 14 days of curing).

After measuring the deformation behaviour in terms of shrinkage and creep, the performance of concrete in reversibility and irreversibility after rewetting and unloading the samples are investigated [49]. In the case of shrinkage, it can be categorized into reversible shrinkage, which is the part of total shrinkage that is reproducible on wet-dry cycles; and irreversible shrinkage, which is the part of total shrinkage on first drying that, cannot be reproduced on subsequent wet-dry cycles. The reversible shrinkage is probably due to development of chemical bonds within *CSH* structure. The irreversible part of shrinkage is associated with the formation of additional physical and chemical bonds in the cement gel when absorbed water has been removed [47]. The case on creep is similar. The developments of shrinkage and creep are illustrated in Figure 4. It can clearly illustrate that the development of the curves of shrinkage and creep in the samples are very similar as that in Figure 4.

<Figure 4>

In this research, rewetting and unloading the samples are exercised after 28 days of measurement. The results show that the reversible parts of shrinkage and creep gained from TSMA are better than those from NMA (see Table 8). For example, 28.70% and 51.11% can be reversed for TSMA and 24.56% and 51.02% can be reversed for NMA on shrinkage and creep respectively with 100% RA substitution after 182 days of curing. However, the difference between 0% and 20% RA substitution is not significant.

<Table 8>

2.2.2 Permeability

Penetration into and leaching out of concrete by materials in solution may adversely affect its durability, for instance when Calcium Hydroxide [$Ca(OH)_2$] is being leached out or an attack by aggressive liquids takes place. This penetration depends on the permeability of the concrete, which is defined as the property that governs the rate of flow of a fluid into a porous solid [32] [44] [47] [48] [57] [58]. Since permeability determines the relative ease with which concrete can become saturated with water, permeability has an important bearing on the vulnerability of concrete to frost. Furthermore, in the case of reinforced concrete, the ingress of moisture and of air and chloride will result in the corrosion of steel. Since this leads to an increase in the volume of the steel, cracking and spalling of the concrete cover may well follow [49]. In this paper, three types of permeability tests are experimented: water permeability, air permeability and chloride permeability. Tables 9, 10 and 11 summarize the results on water, air and chloride permeability respectively.

<Table 9>

<Table 10>

<Table 11>

In a hydrated cement paste, the size and continuity of the pores at any point during the hydration process would control the coefficient of permeability. The mixing water is indirectly responsible for permeability of the hydrated cement paste because its content determines the total space and subsequently the unfilled space after the water is consumed by either cement hydration reactions or evaporation to the environment [47]. The permeability of concrete is affected by its porosity, and size, distribution and continuity of the pores [49]. The experimentation highlights the reduction on the performance of permeability with higher substitutions of RA (see Tables 9, 10 and 11). For examples, the water, air and chloride permeabilities obtained are 0.001642mm^2/s.BAR, 4.5470s/ml and 2906.60 amperes.s with 100% RA substitution compared to 0.001284mm^2/s.BAR, 9.0082s/ml and 2231.56 ampere.s with 0% RA substitution for NMA under 182 curing conditions. However, the difference is not significant for RA replacements between 0% and 20%.

Although the adoption of RA will weaken the performance of RAC [24] [32], TSMA helps alleviate the problem as a reduction in the volume of large capillary voids in the paste matrix would certainly reduce the permeability. Since the porosity of RA is reduced by the provision of the cement gel surrounding RA in the pre-mix stage of TSMA, permeability can be improved (see Tables 9, 10 and 11). For examples, the water, air and chloride permeability obtained are 0.001544mm^2/s.BAR, 9.7374s/ml and 2906.60 amperes.s for NMA compared with 0.001501mm^2/s.BAR, 11.2817s/ml and 2578.04 ampere.s for TSMA on 20 percent of RA substitution under 182 curing conditions. Furthermore, the improvement of TSMA can be up to 35.41% on water permeability (as in the case of 100% RA substitution after 126 days of curing), 51.81% on air permeability (as in the case of 20% RA substitution after 56 days of curing) and 29.98% on chloride permeability (as in the case for 100% RA substitution after 126 days of curing).

From the above tests, it is obvious that TSMA can help improve the durability, in terms of deformation and permeability, of the RAC. During the first stage of mixing, TSMA uses only half of the water for mixing to form 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 [Figures 5 shows the filled crack after using TSMA, while Figure 6 shows the unfilled crack after using NMA]. At the second stage of mixing, the other half of water is added to complete the concrete mixing process. The experimentation shows that TSMA can enhance the performance of RAC by the development of a stronger interfacial zone in comparison with the traditional process (see Figure 7 for TSMA and Figure 8 for NMA). 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 investigation, the results are difficult to reconcile. Nonetheless, it is generally agreed that as the paste-aggregate bond strength increases, the concrete strength also increases [48]. Figure 9 highlights the fracture mode for TSMA which is not around ITZ, while that for NMA is. It is therefore proved that TSMA can improve the ITZ of RA and thus the strength and durability of RAC. Figure 10 illustrates the concrete matrix scenario for NMA and TSMA schematically.

<Figure 5>

< Figure 6>

< Figure 7>

< Figure 8>

< Figure 9>

< Figure 10>

3. Conclusion

The poor quality of RAC resulted from higher water absorption, higher porosity, weaker ITZ between RA and new cement mortar hampers the application of RAC for higher grade applications. Two-Stage Mixing Approach (TSMA) has been proposed by Tam *et al.* [1] to strength the weak link of RAC, which is located at the Interfacial Transition Zone (ITZ) of the RA. The TSMA allows the cement slurry to gel up the RA, providing a stronger ITZ by filling up the cracks and pores within RA. The improvements of strength after adopting TSMA have been proven by the works of Tam *et al.* [1]; the durability on deformation and permeability have been explored in this paper. Experimentation highlights that:

(a) The higher the substitutions of RA, the weaker the performance of RAC; and

(b) The deformation and permeability of RAC can be enhanced by adopting TSMA with up to

 (i) 68.09% on shrinkage (with 100% RA substitution after 14 days of curing);

 (ii) 46.42% on creep (with 100% RA substitution after 14 days of curing);

 (iii) 35.41% on water permeability (with 100% RA substitution after 126 days of curing);

 (iv) 51.81% on air permeability (with 20% RA substitution after 56 days of curing); and

 (v) 29.98% on chloride permeability (with 100% RA substitution after 126 days of curing).

Therefore, this demonstrates that TSMA can provide an effective method for enhancing durability, in addition to the previously verified strength improvement, and thus the approach opens up a wider scope of RAC applications.

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Table 1: Reuse of Demolished Concrete [7]

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 2: Mix Proportions [39]

Ingredients of concrete	Mass (in kg)
Ordinary Portland cement	100
Fine aggregate	180
20mm coarse aggregate	180
10mm coarse aggregate	90
Water	45

Table 3: Standards Controlling the Properties of Concrete

Properties of Concrete	Standard
Deformation	
Shrinkage	BS 1881: Part 5 [59]
Creep	ASTM C512-02 [60]
Permeability	
Water permeability	Manual of GWT-4170 kit
Air permeability	Manual of P-6000 Poroscope
Chloride permeability	American Association of State Highway and Transportation Officials T277 [61]

Table 4: Parameters Affecting Deformation of Concrete [48]

Paste parameters	Porosity Age of paste Curing temperature Cement composition Moisture content Admixtures
Concrete parameters	Aggregate stiffness Aggregate content Volume-surface ratio Thickness
Environmental parameters	Applied stress Duration offload Relative humidity Rate of drying Time of drying

Table 5: Shrinkage Results for RAC

Days	Shrinkage (in %)					
	NMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	0.005%	0.007%	0.011%	0.011%	0.006%	0.003%
28	0.019%	0.015%	0.022%	0.021%	0.014%	0.014%
42	0.049%	0.044%	0.051%	0.046%	0.047%	0.035%
56	0.062%	0.075%	0.070%	0.064%	0.062%	0.062%
70	0.072%	0.074%	0.080%	0.070%	0.078%	0.074%
84	0.078%	0.080%	0.091%	0.083%	0.083%	0.089%
98	0.083%	0.088%	0.096%	0.086%	0.089%	0.092%
112	0.095%	0.095%	0.103%	0.095%	0.095%	0.100%
126	0.099%	0.102%	0.110%	0.101%	0.102%	0.108%
140	0.108%	0.109%	0.118%	0.112%	0.110%	0.116%
154	0.114%	0.115%	0.125%	0.117%	0.115%	0.120%
168	0.120%	0.118%	0.128%	0.121%	0.118%	0.126%
182	0.121%	0.123%	0.131%	0.124%	0.122%	0.129%
Rewetting						
189	0.098%	0.095%	0.106%	0.100%	0.093%	0.099%
196	0.089%	0.088%	0.101%	0.091%	0.088%	0.095%
203	0.088%	0.087%	0.100%	0.088%	0.086%	0.093%
210	0.088%	0.086%	0.099%	0.087%	0.085%	0.092%
Note: The specimens are wetted for the first 28 days for curing; and then dried until day 182. After day 182, rewetting for another 28 days (until day 210) is undertaken.						

Table 6: Creep Strain and Creep Coefficient for RAC

t	CS_t^*						CC_t^*					
	NMA			TSMA			NMA			TSMA		
	0%	20%	100%	0%	20%	100%	0%	20%	100%	0%	20%	100%
14	0.000146	0.000215	0.000461	0.000133	0.000134	0.000247	1.46	2.15	4.61	1.33	1.34	2.47
28	0.000219	0.000320	0.000669	0.000216	0.000238	0.000493	2.19	3.20	6.69	2.16	2.38	4.93
42	0.000291	0.000398	0.000799	0.000280	0.000301	0.000630	2.91	3.98	7.99	2.80	3.01	6.30
56	0.000326	0.000459	0.000930	0.000323	0.000361	0.000741	3.26	4.59	9.30	3.23	3.61	7.41
70	0.000371	0.000517	0.001040	0.000373	0.000396	0.000822	3.71	5.17	10.40	3.73	3.96	8.22
84	0.000390	0.000557	0.001117	0.000404	0.000457	0.000902	3.90	5.57	11.17	4.04	4.57	9.02
98	0.000443	0.000597	0.001196	0.000430	0.000488	0.000952	4.43	5.97	11.96	4.30	4.88	9.52
112	0.000473	0.000636	0.001267	0.000445	0.000528	0.001003	4.73	6.36	12.67	4.45	5.28	10.03
126	0.000501	0.000667	0.001335	0.000482	0.000559	0.001058	5.01	6.67	13.35	4.82	5.59	10.58
140	0.000510	0.000691	0.001376	0.000485	0.000569	0.001102	5.10	6.91	13.76	4.85	5.69	11.02
154	0.000533	0.000725	0.001441	0.000502	0.000593	0.001132	5.33	7.25	14.41	5.02	5.93	11.32
168	0.000549	0.000753	0.001486	0.000517	0.000618	0.001176	5.50	7.53	14.86	5.17	6.18	11.76
182	0.000563	0.000754	0.001517	0.000530	0.000633	0.001176	5.63	7.54	15.17	5.230	6.33	11.76
Unloading												
7 days	0.000038	0.000189	0.000806	0.000012	0.000079	0.000722	0.38	1.89	8.06	0.12	0.79	7.22
14 days	0.000019	0.000161	0.000782	0.000012	0.000054	0.000667	0.19	1.61	7.82	0.12	0.54	6.67
21 days	0.000017	0.000140	0.000761	0.000012	0.000041	0.000610	0.17	1.40	7.61	0.12	0.41	6.10
28 days	0.000015	0.000129	0.000743	0.000012	0.000024	0.000575	0.15	1.29	7.43	0.12	0.24	5.75

Note:

^ The specimens are loaded for the first 182 days; and then unloaded for another 28 days (until day 210).

* The creep strain and creep coefficient are measured by *Equations (1)* and *(2)* respectively.

$$CS_t = \varepsilon_t - \frac{1}{E} - S_t \qquad \textit{Equation (1)}$$

.

$$CC_t = \frac{CS_t}{\frac{1}{E}} \qquad \textit{Equation (2)}$$

Where CS_t is the creep strain at time t; CC_t is the creep coefficient at time t; ε_t is the measured strain at time t; $\frac{1}{E}$ is the initial elastic strain; S_t is the shrinkage strain at time t; and t is the time after loading (in days).

Table 7: Creep Constant for RAC

Creep Constant*	NMA			TSMA		
	0%	20%	100%	0%	20%	100%
$\frac{1}{E}$	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
F(K)	0.00002	0.00003	0.00005	0.00002	0.00002	0.00005

Note:

* The creep constant of initial elastic strain ($\frac{1}{E}$) and creep rate [F(K)], can be estimated by fitting a curve in *Equation (3).*

$$\varepsilon_t = \left(\frac{1}{E}\right) + F(K) In(t+1) \qquad \textit{Equation (3)}$$

Where ε_t is the measured strain at time t; $\frac{1}{E}$ is the initial elastic strain; *F(K)* is the creep rate (in strain/day); and *t* is the time after loading (in days).

Table 8: Reversible and Irreversible Parts on Shrinkage and Creep

Mixing Method		Percentage (%)					
		NMA			TSMA		
		0%	20%	100%	0%	20%	100%
Shrinkage	Reversible	27.73%	29.98%	24.56%	27.88%	30.00%	28.70%
	Irreversible	72.27%	70.02%	75.44%	72.12%	70.00%	71.30%
Creep	Reversible	97.34%	82.89%	51.02%	97.74%	96.21%	51.11%
	Irreversible	2.66%	17.11%	48.98%	2.26%	3.79%	48.89%

Table 9: Water Permeability for RAC

Curing days	Water permeability (in mm^2/s.BAR)					
	NMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	0.00786	0.00723	0.00887	0.00716	0.00737	0.00722
28	0.00734	0.00832	0.00719	0.00697	0.00813	0.00678
42	0.00733	0.00737	0.00723	0.00673	0.00770	0.00744
56	0.00747	0.00855	0.00786	0.00728	0.00793	0.00866
70	0.00829	0.00114	0.00150	0.00131	0.00121	0.00146
84	0.00120	0.00121	0.00140	0.00109	0.00122	0.00113
98	0.00152	0.00117	0.00137	0.00111	0.00121	0.00120
112	0.00132	0.00163	0.00144	0.00101	0.00117	0.00122
126	0.00134	0.00128	0.00172	0.00132	0.00113	0.00111
140	0.00173	0.00152	0.00142	0.00124	0.00144	0.00162
154	0.00139	0.00144	0.00140	0.00129	0.00152	0.00140
168	0.00138	0.00162	0.00140	0.00147	0.00147	0.00164
182	0.00128	0.00154	0.00164	0.00139	0.00150	0.00147

Note:
The measurement of water permeability changed during the test period; a double-line in separated the results.

Table 10: Air Permeability for RAC

Curing days	Air permeability (in s/ml)					
	NMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	9.64	10.81	6.73	12.54	12.72	7.91
28	13.90	11.12	7.10	14.15	14.70	8.77
42	13.65	10.04	7.60	12.18	12.61	10.94
56	10.603	8.28	4.72	12.01	12.57	6.99
70	10.55	9.74	5.75	11.67	10.34	6.26
84	8.84	10.77	6.35	11.67	11.97	5.40
98	9.65	11.45	7.08	11.28	10.55	6.61
112	11.28	9.27	4.80	12.18	11.28	6.31
126	11.50	9.10	6.35	12.05	11.32	5.83
182	9.01	9.74	4.55	11.24	11.28	6.56

Table 11: Chloride Permeability for RAC

Curing days	Chloride permeability (in amperes.s)					
	NMA			TSMA		
	0%	20%	100%	0%	20%	100%
14	3753.29	3153.53	3800.54	3248.91	3827.90	3617.31
28	2468.93	3054.11	2931.48	2436.47	2487.39	3394.85
42	2475.68	3025.79	3199.16	2409.26	2301.60	2697.59
56	2636.46	2269.97	2629.22	2100.35	2911.52	2778.94
70	2405.66	2606.84	2243.48	2137.37	2414.94	2455.22
84	2337.51	2410.25	2947.68	2097.71	2728.77	2481.16
98	2427.69	2615.16	2257.86	1927.43	2596.97	2313.65
112	2627.20	2766.39	3155.49	2031.45	2739.06	2683.31
126	2741.46	2211.87	3330.50	2021.21	2811.89	2331.85
182	2231.56	2703.69	2906.60	1869.96	2121.95	2578.04

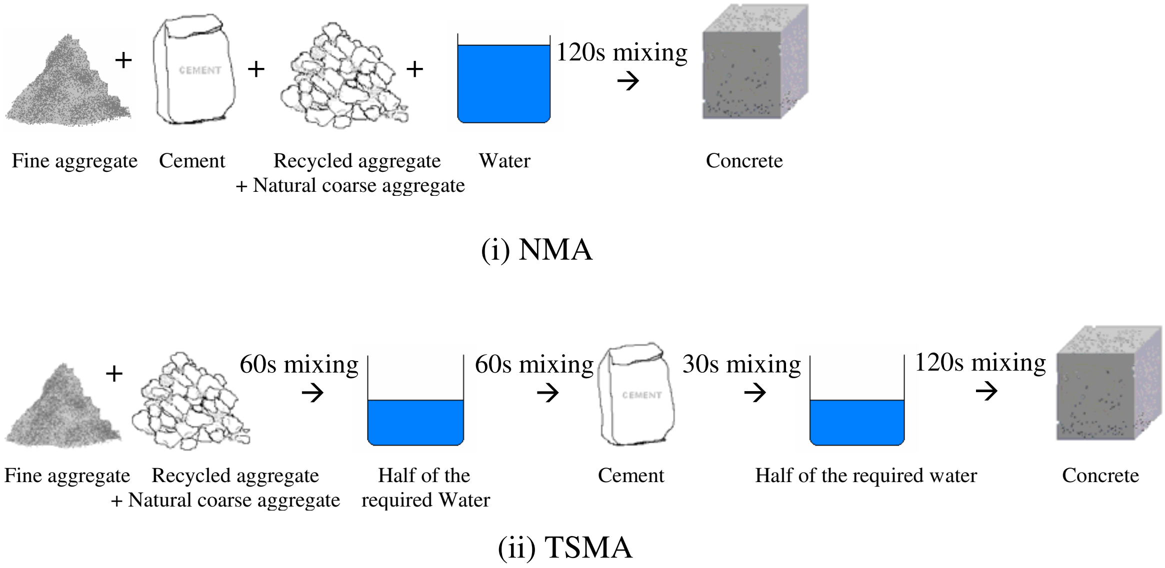
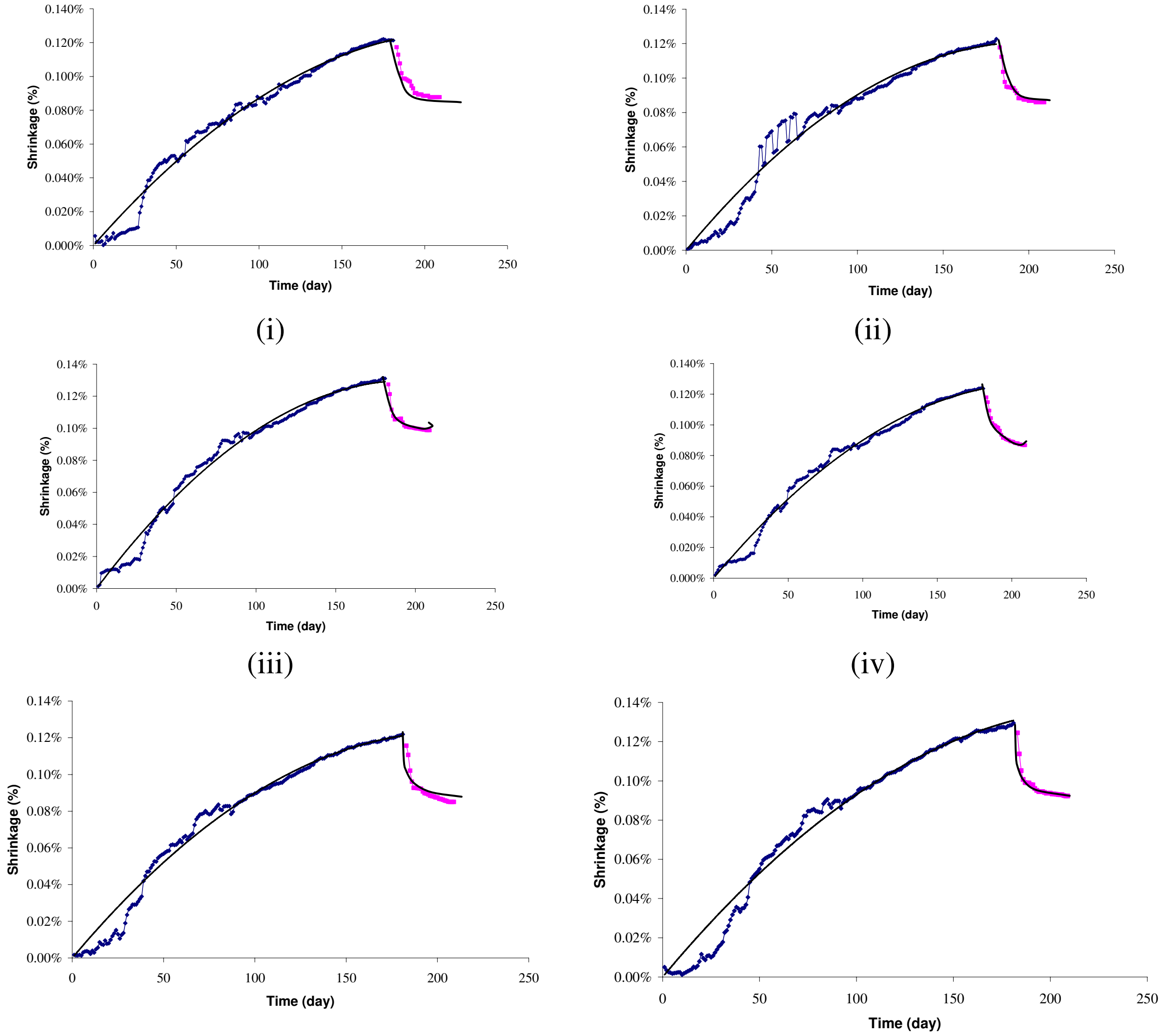


Figure 1: Mixing Procedures of the (i) Normal Mixing Approach and

(ii) Two-Stage Mixing Approach



(vi)

Figure 2: Shrinkage deformation behaviour on i) 0% RA replacement for NMA; ii) 20% RA replacement for NMA; iii) 100% RA replacement for NMA; iv) 0% RA replacement for TSMA; v) 20% RA replacement for TSMA; and vi) 100% RA replacement for TSMA

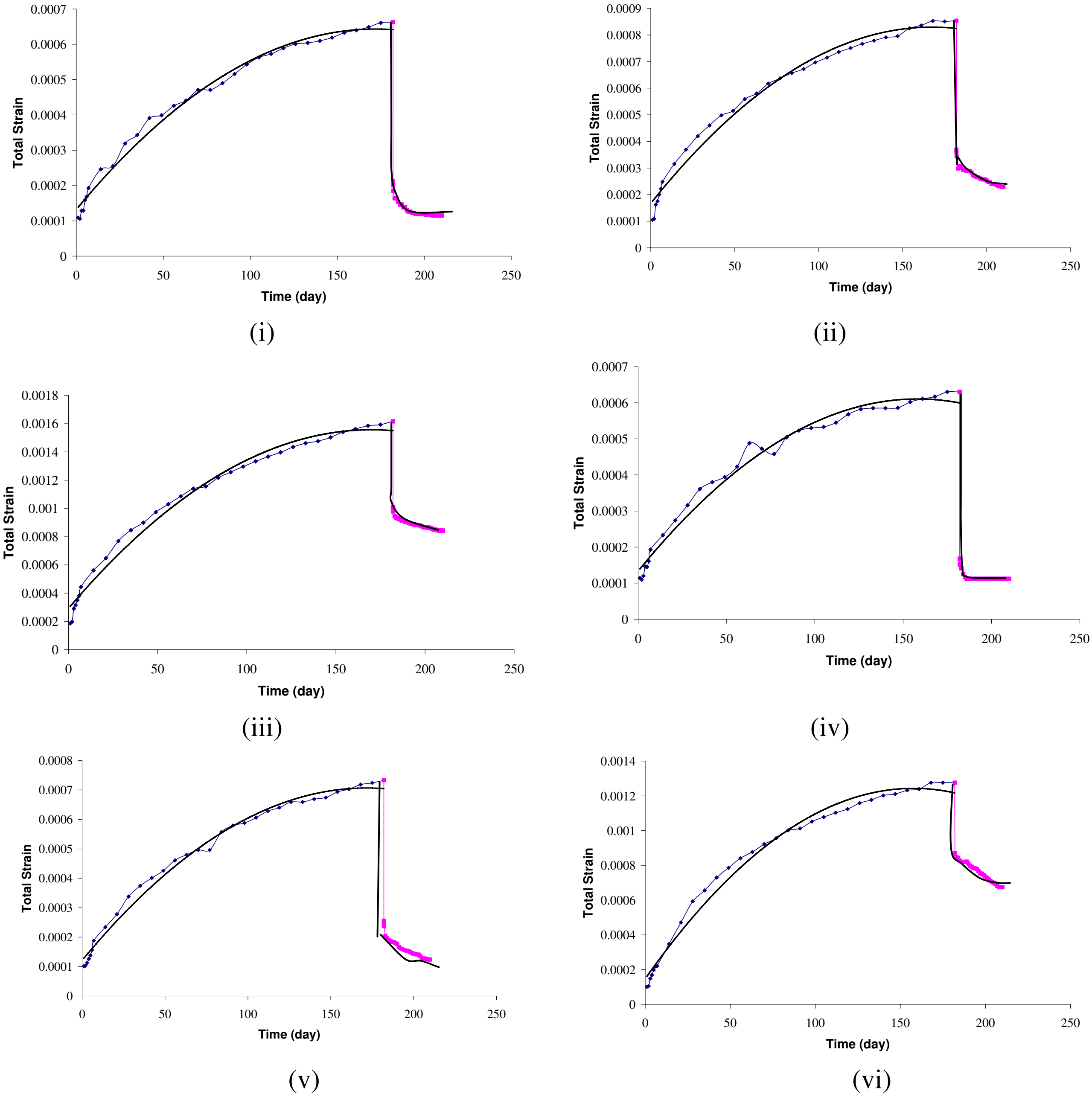
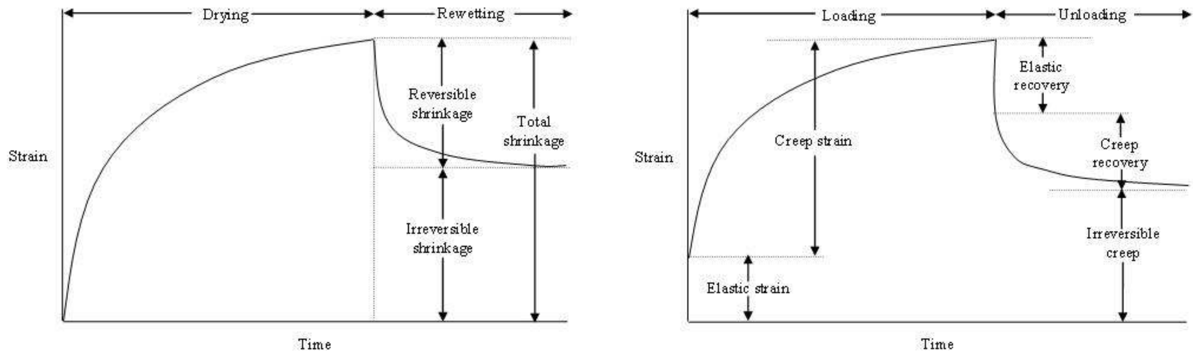


Figure 3: Creep deformation behaviour on i) 0% RA replacement for NMA; ii) 20% RA replacement for NMA; iii) 100% RA replacement for NMA; iv) 0% RA replacement for TSMA; v) 20% RA replacement for TSMA; and vi) 100% RA replacement for TSMA



(i) (ii)

Figure 4: Development of (i) Shrinkage; and (ii) Strain, in Concrete [47]

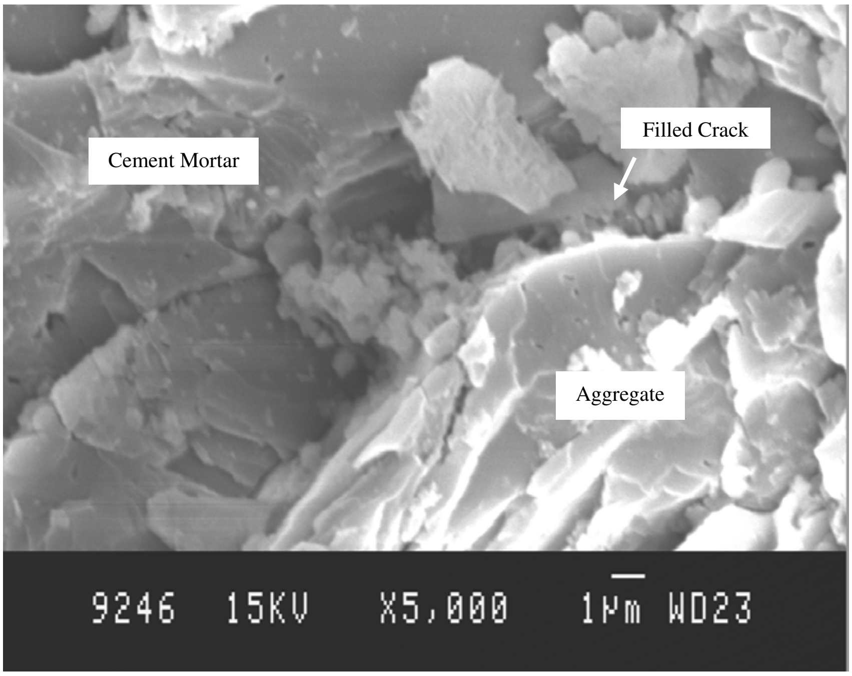


Figure 5: Filled Crack in RA using TSMA

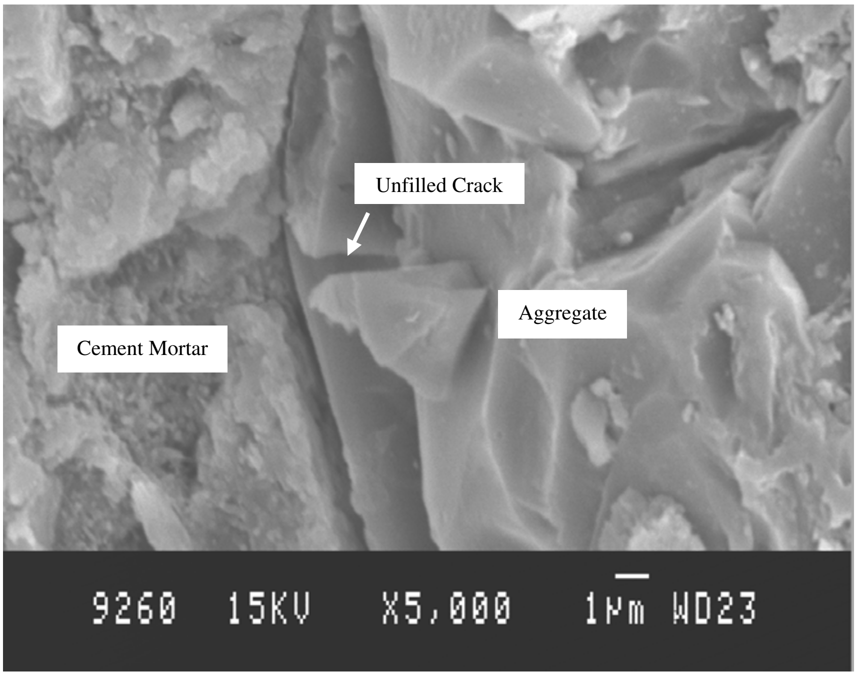


Figure 6: Unfilled Crack in RA using NMA

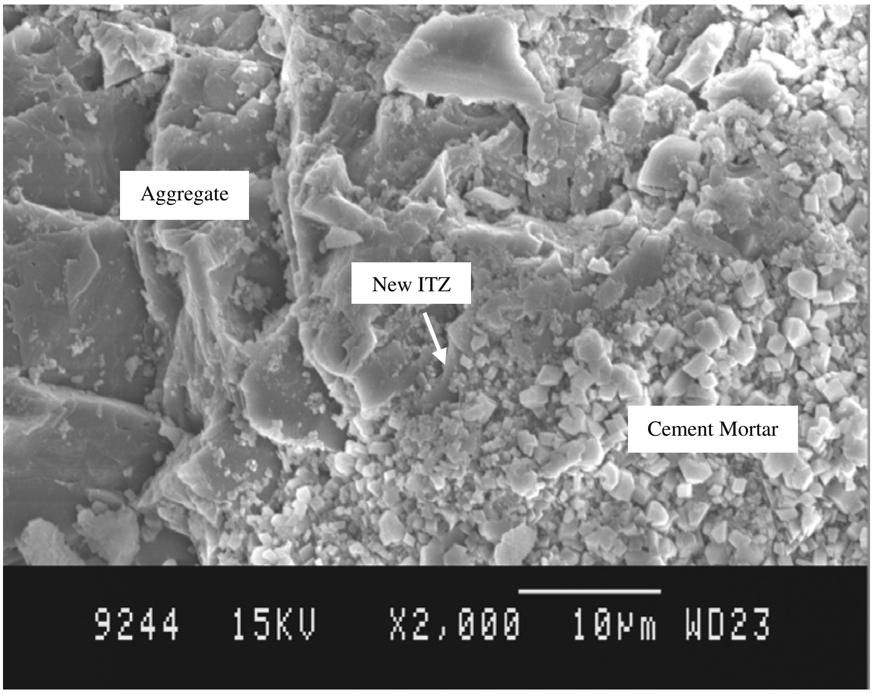


Figure 7: New Interfacial Zone for TSMA

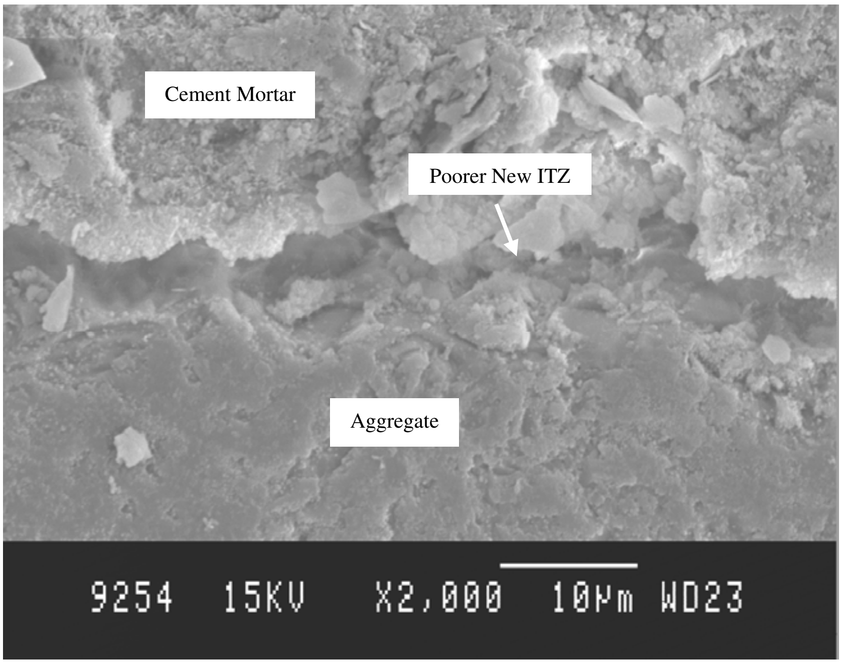


Figure 8: Poorer New Interfacial Zone for NMA

(i) (ii)

Figure 9: Fracture Mode on (i) TSMA; and (ii) NMA

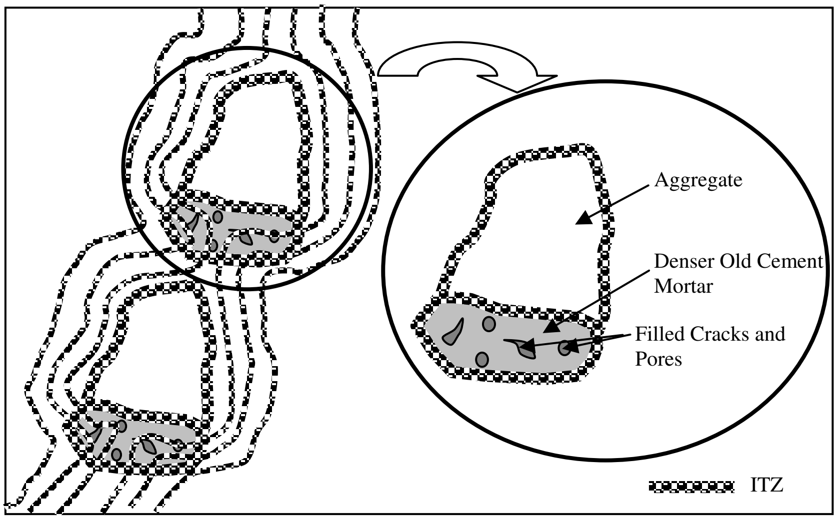


Figure 10: RA Structure after Adopting TSMA