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Fracture and Failure of Recycled Aggregate Concrete (RAC) – A Review

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Abstract
In the world, many countries put into effect the renewal plans and/or the laws and/or the regulations for recent engineering structures which have reached their lifetime, are risk prone and have been built lacking quality engineering, or without considering urban planning. Hence, many structures are demolished and this situation increases the amount of construction and demolition waste (C & DW). Also, resource consumptions are rapidly increased due to excessive constructional works. As a result of wide-spreading sustainability concept in the world, it is commenced that C & DW is used as recycled aggregate in engineering structures and is used in concrete to struggle with shortage of aggregate resources. In this perspective, researches are conducted to determine the engineering parameters of recycled aggregate (RA) and recycled aggregate concrete (RAC). The mentioned unfavorable situations in this literature research are cracked and fissured structure of RA and its negative effect on RAC. With regards to this, the present paper reviews the literature related to the fracture and failure of RAC and mainly the related topics are based on internal structure properties of RA and fracture behavior of RAC. According to researches, interfacial transition zone (ITZ) and RA properties are more effective on the cracks and the fracture modes formations. Some methods (for example, mixing methods, surface coating methods) are proposed in the literature to enhance the negative effects of RA on RAC. Also the researches on the fracture due to fatigue of RAC, is found to be very limited in the literature.

Keywords: *C & DW, recycled aggregate concrete, crack, ITZ, fracture, fatigue*

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INTRODUCTION

Concrete is one of the most useful and basic materials in 21st century in the world. In many civil engineering works, concrete plays a vital role due to shapeable, economic properties. Also the advancement of civilizations is contributed by the versatility of concrete through history[1, 2]. The contribution resourced by concrete lies in the parameters of concrete (i.e., its high strength, resistant to weathering conditions, excellent structural behavior etc.)[2]. Nowadays, desired strength of concrete for structures can be obtained in plants utilizing various additions (e.g., mineral additions) and transportation of concrete from the plant to the construction area is done by trans-mixers with ease.

The common production and the common use of concrete results in the extensive increase in the urbanization rate and that are proportional to the global economic and population growth. This situation has made concrete a headliner in the economy development of a country due to huge amount of usage[2]. It is estimated that 20 billion metric tons concrete is currently used per annum, 26 billion tons aggregate consumption may be exceeded by 2012 and it will increase in future as well[2]. Increasing human demands and excessive consumption, results in the decrease of natural resources in the world. In this situation, humankind commences to solve the resource scarcity by reusing materials. Hence, in many areas, material reuse opinion known as recycling is widely accepted all over the world. In the construction area, concrete is commonly used in many engineering structures and, hereby most of demolished structures consist of concrete. In this view, construction and demolition waste (C & DW) includes mostly concrete and rarely other materials (i.e., brick, marble, polyvinyl chloride (PVC) and wood). Hence, nowadays C & DW is used as recycled aggregate (RA) in concrete and has become a subject of interest for many researches.

Recently, C & DW increases more and more as a result of excessive consumption. Also, in some countries, engineering structures are risk prone (i.e., flood disaster, earthquake) or have reached the lifetime, or have been built lacking quality engineering, and/or built without considering urban planning. According to the renewal plans and/or laws and/or regulations, the structures are then demolished[1,3] and this results in the increase of C & DW worldwide. Hence, it is commenced that RA should be used in engineering structures to dispose the wastes and overcome shortage of aggregate resources. For instance, according to the European Union Directive (Directive No. 2008/98/EC), it is set that minimum proportion of reuse of C & DW is 70% beyond 2020[4]. In this view, engineering properties of RA should be known before use and many researches have already begun to determine the parameters of RA and RAC.[2,3,5–7]

Concrete and concrete elements usually fail due to cracks and crack propagations before ultimate load is reached. In this perspective, the failure and fracture mechanics should be taken into account while structures are being designed, especially concrete structures, and it also has an importance in building the engineering structures safely and economically. In addition, material specifications (i.e., ductility, strength) have a vital role. The information about fracture and failure mechanisms of RA, and its effects on the concrete should be well-known before use.

Although many researchers have studied this subject to determine the properties of recycled aggregate concrete (RAC) and review papers on some properties of RAC such as physical and mechanical properties have been examined in the literature[3,5,6], the properties of RAC such as failure and fracture, are rarely reviewed[7.8]. To fill this gap in the literature, the present paper aims to review the literature related to the fracture and the failure of RAC. Mainly the related topics in this review paper are based on the RA properties (i.e., interfacial transition zone (ITZ), crack types and the fracture properties of RAC like cracking angle. Also, some evolved methods for example double mixing method to enhance the poorer properties of RA and RAC, advances in the observation methods (e.g., microscopy) and its applications on RA and RAC are presented.

STUDIES ON RA AND RAC

Recycling Process

Reuse of materials, is called as recycling. Recycling of C & DW includes basic two simple steps: The first step is breaking C & DW to produce smaller size fragments and the second step is sorting. Removing contaminants can be included in the first or second step. C & DW is formed as RA using various types of crushers such as hammer mill, jaw crusher, impact crusher *etc*.[5] It is reported by Etxeberria M. *et al*.[9] that jaw crushers are generally utilized for primary crushing that are able to crush oversized concretes into small pieces for second crushing process while second crushing process may be needed. Impact crushers are chosen to obtain better quality aggregates and less attached mortar content on aggregate[9]. However, due to the effectiveness of crushing process, the physical and mechanical properties of RA are affected by different crushers[2]. In the breaking step of crushing process, usually C & DW is subjected to forces and the discontinuities like cracks occur in the structure of RA[1].

High water absorption rate may be caused due to various factors and one of the factors can be crushing process. It is well-known that first step of aggregate production is breaking big parts of rocks to produce smaller size fragments using various type of productions. Hence, old aggregate part of RA may have discontinuities in the structure due to first production step.

On the contrary, some techniques are evolved to decrease the negative effect of RA on concrete[10–18] (i.e., by microwave heating method, freeze-thaw method, thermal expansion method, ultrasonic treatment method). As a result of utilization of these advanced techniques, better quality aggregate production is possible by removing the attached old mortar paste.

Hence, original aggregate is obtained without losing integrity of aggregate. Although no force is applied to RA in the former methods mentioned above, it is possible that cracks or discontinuity may occur in RA by treatment effects for example, microwave effects of the latter mentioned techniques. Hence, the advanced techniques can be preferred over other methods (i.e., jaw crushing).

RA, Composition of RA and RAC

Many properties of the concrete are related to whether the hardened cement paste and ITZ are of good quality. Cement with water forms the hardened cement paste by the time and the paste is constituted by hydrate phases, anhydrous phases (mineral additions, un-reacted clinker minerals) and minor phases (hydro-talkite, pores, and pore solution)[8]. The hydrate phase is more common in the hardened paste, and it is named as calcium silicate hydrate (C–S–H)[8]. In pending hydration and service life of the concrete, water is able to move in or out the concrete due to ambient conditions and hence, hydration can result in the self-desiccation due to absence of necessary water content in concrete and leads to inevitable shrinkage of concrete[8]. Hence, concrete properties are affected negatively. This situation affects the concrete structure and leads to cracks in old cement paste of RA due to the water movement.

It is well-known that RAC includes three phases: the mortar phase (old and new mortar), the aggregate phase (old and new aggregate) and the interfacial transition zone between the (old and/or new) aggregate and the (old and/or new) mortar as represented in Figure 1[2]. These phases influence the behavior of concretes, especially failure mode of RAC. RAC is different from natural aggregate concrete (NAC) as RAC has two ITZs: one is new ITZ (between RA and new matrix) and another is old ITZ (between RA and old adhered mortar) as depicted in Figure 2[2]. Hence, the performance of the ITZs influences the mechanical performance of RAC[2].

Moreover, RA is produced by processing of the debris which is generated from the C & DW and other applications such as concrete members of rejected precast, concrete road beds, leftover concrete obtained from plants and various laboratories and broken masonry. Due to various resources available, the RA composition may vary from brick aggregates to glass aggregates, from concrete particles to tiles and marbles, from metals to ceramic products, and from paper to plastic, etc. Hence, all the materials/products used in the construction are possible to be used as a RA. Usually RA is mixed with impurities like brick, tiles etc. The amount of impurities may be strictly variable on RAC properties[19], the impurities in RA determine the fracture zone of RAC due to their lower strength properties than the hardened paste[19]. Use of C & DW in concrete as RA concept came into existence a few decades ago after the World War II in Europe[20–23]. Recently, it is being utilized in construction area[1] previously it was used as sub-base material of pavement.

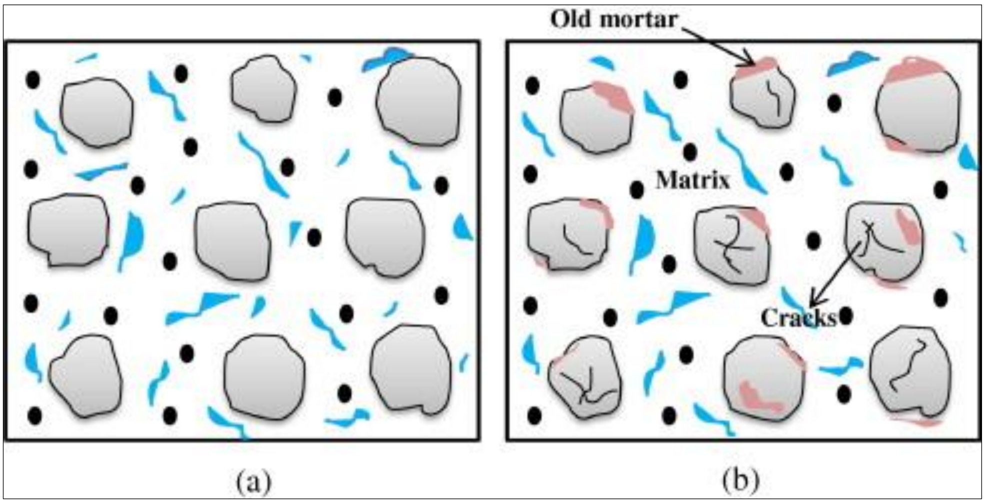

Fig. 1: *Difference between Matrixes of (a) Natural Aggregate Concrete and (b) Recycle Aggregate Concrete*[2].

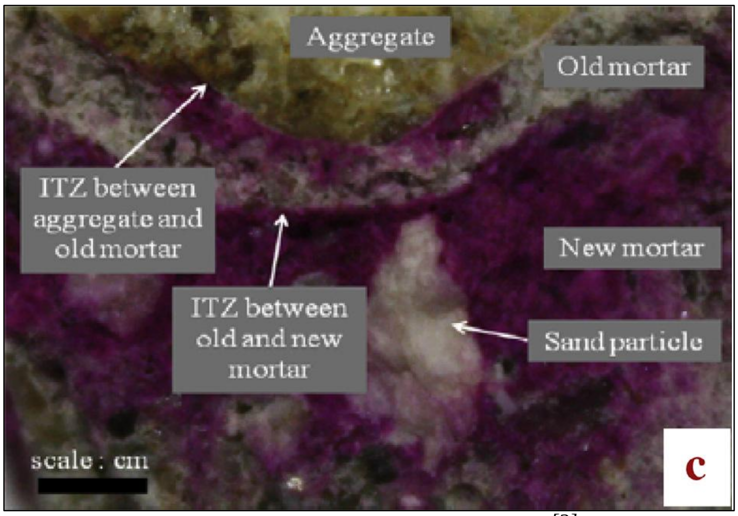

Fig. 2: *Sectional View of RAC* [2].

Crack and Failure

The crack pattern and failure of concrete elements made up with NAC and RAC, and the concretes included RA at various ratios are examined by many researchers[24–28] and studied RAC beams are subjected to low velocity impact[25]. According to the research done by Rao *et al.*[25] the crack is initiated at the bottom of beams vertically at or near the impact point in both NAC and RAC is shown in Figure 3. After the initiation of crack, the beams immediately failed as represented in Figure 3. The crack surface is demonstrated in Figure 4[25] which indicates that the failure occurred at the weakest point i.e., RA for RAC and ITZ for NAC. It can also be concluded from Rao *et al.*[25] that the recycled coarse aggregates are relatively finer and the surface texture is more porous and rough than NA.

Hence, the failure path is more even in case of RAC and the failure occurs through the aggregates. On the contrary, Xiao *et al.*[26] produced RAC with various replacement ratios (0–30–50–70–100%) of aggregate with RA. According to their study, the inclination angle of macro-cracks was examined. The experimental results indicate that the angle obtained for NAC with respect to the vertical loading plumb is approximately 58–64^{o}. However the angle obtained for RAC is about 63–79^{o}.

Hence, the inclination angle of the failure plane of RAC is considerably bigger than that of NAC. The failure process and failure pattern of RAC is demonstrated in Figure 5. Also, in this experimental study, fracture of RA and NA are rarely observed and it is concluded that the failure mode of RAC is shear mode.

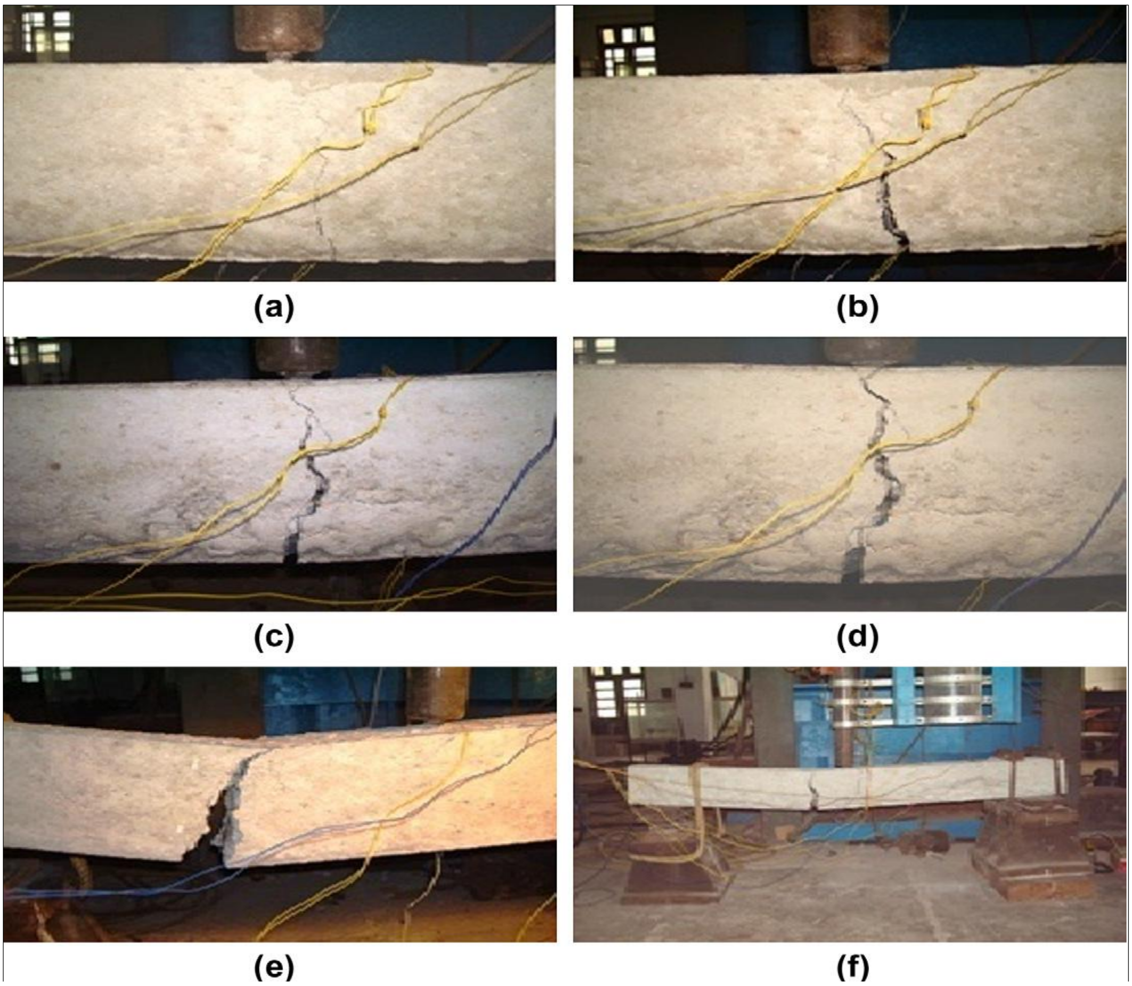

Fig. 3: *Crack Pattern of both Normal and Recycled Aggregate Concrete Beams: (a) and (b) are Normal Concrete, (c) RAC with 25% RCA, (d) RAC with 50% RCA, (e) and (f) RAC with 100% RCA*[25].

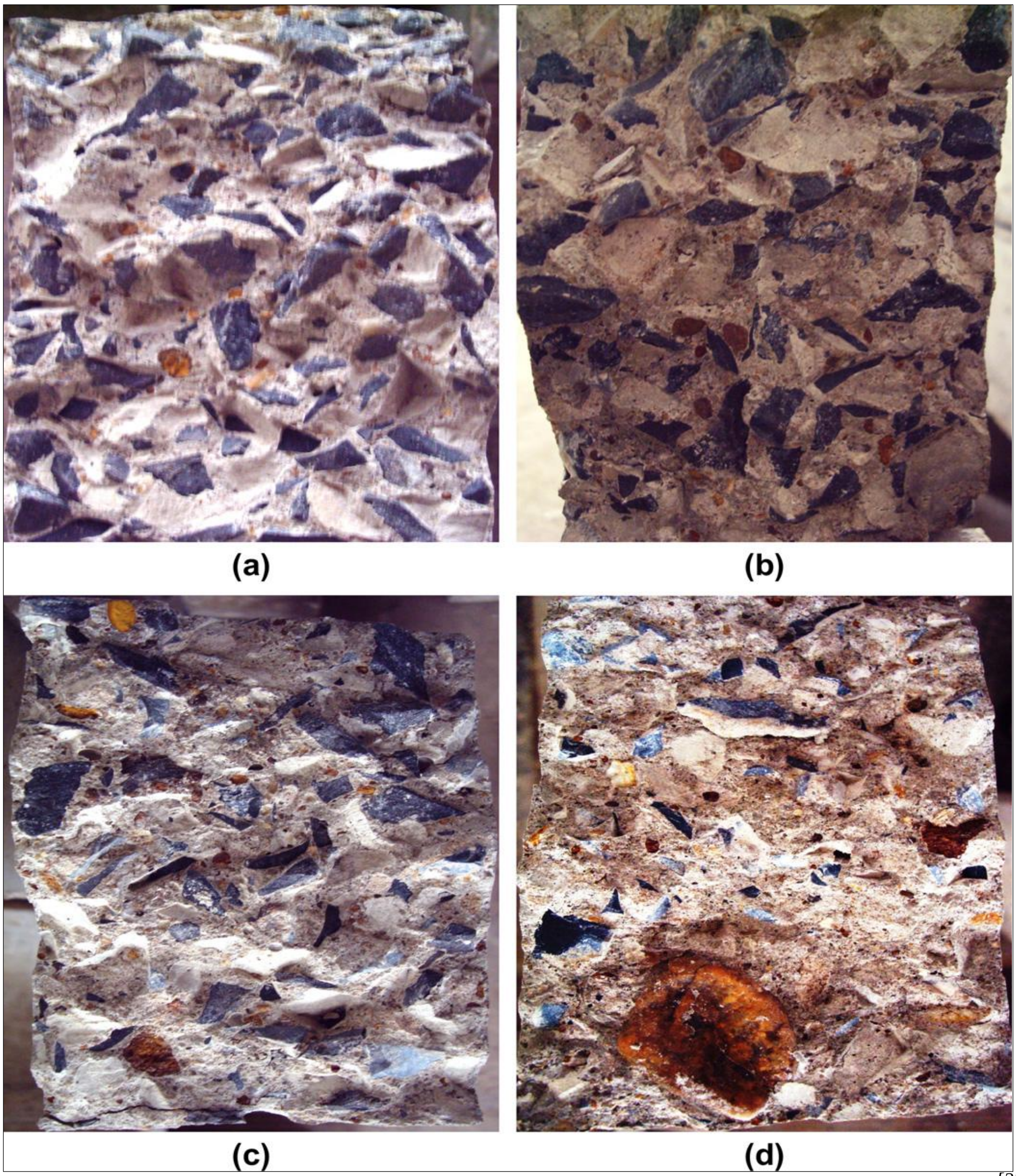

Fig. 4: *Failure Surfaces of: (a) M-RAC0 (b) M-RAC25 (c) M-RAC50 and (d) M-RAC10*[25].

Fig. 5(a): *Failure Process and Failure Pattern.*

***Fig. 5(b):** Failure Process of Recycled Aggregate Concrete Prism*[26].

Mixing Methods, Surface Treatment and Mineral Addition Used in RAC

According to the weaker properties of RAC, some researchers have developed mixing methods in order to improve the properties of RAC and micro-structure of ITZ including double-mixing method and triple-mixing method)[24,29–32]. The enhanced mixing methods focus on the improvement of ITZ of RAC and other properties. The effect of the mixing methods on the RA which has porous structures, cracks and fissures resulted in the filling up of pores and cracks as shown in Figure 6. This results in an improved ITZ of RA and a denser concrete. Hence, according to the improved mixing methods, the fracture may not occur through the RA. Also it is presented, that triple-mixing method enhanced the properties of RAC to higher level in comparison to double-mixing method[24,29].

On the other hand, some researchers used mineral additions like silica fume, fly ash etc. to coat the surface of RA to improve the low properties (i.e., low strengths, low density)[24,33]. Modifying the poorer properties of ITZ of RAC and cement matrix of RAC is aimed by incorporating mineral additions as depicted in Figure 6[2]. When mineral additions are utilized in concrete, they behave as micro-filler and fill the gaps of ITZ. They also provide the secondary C–S–H gel formation in RAC which gives RAC the enhancement of compactness leading to closure of open pores and empty capillary spaces shown in Figure 6[2,24] as secondary C–S–H gel forms the structure of concrete and, of course cement grains are the basic factor for the C–S–H gel formation in the cement paste[8].

Parallel good results are also obtained by other researchers using some other enhanced methods (like ultrasonic cleaning method, heating at first and then rubbing, etc.)[33–35]. However, more energy is needed for the above mentioned methods.

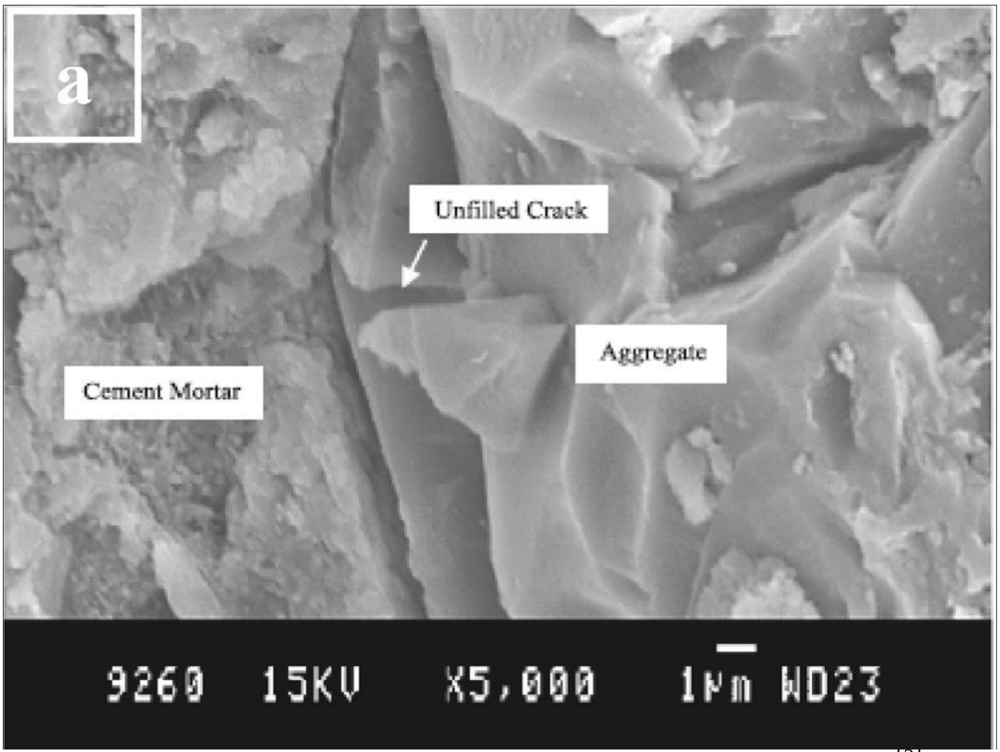

Fig. 6(a): *Unfilled Cracks in RA by Two Stage Mixing Approach[2].*

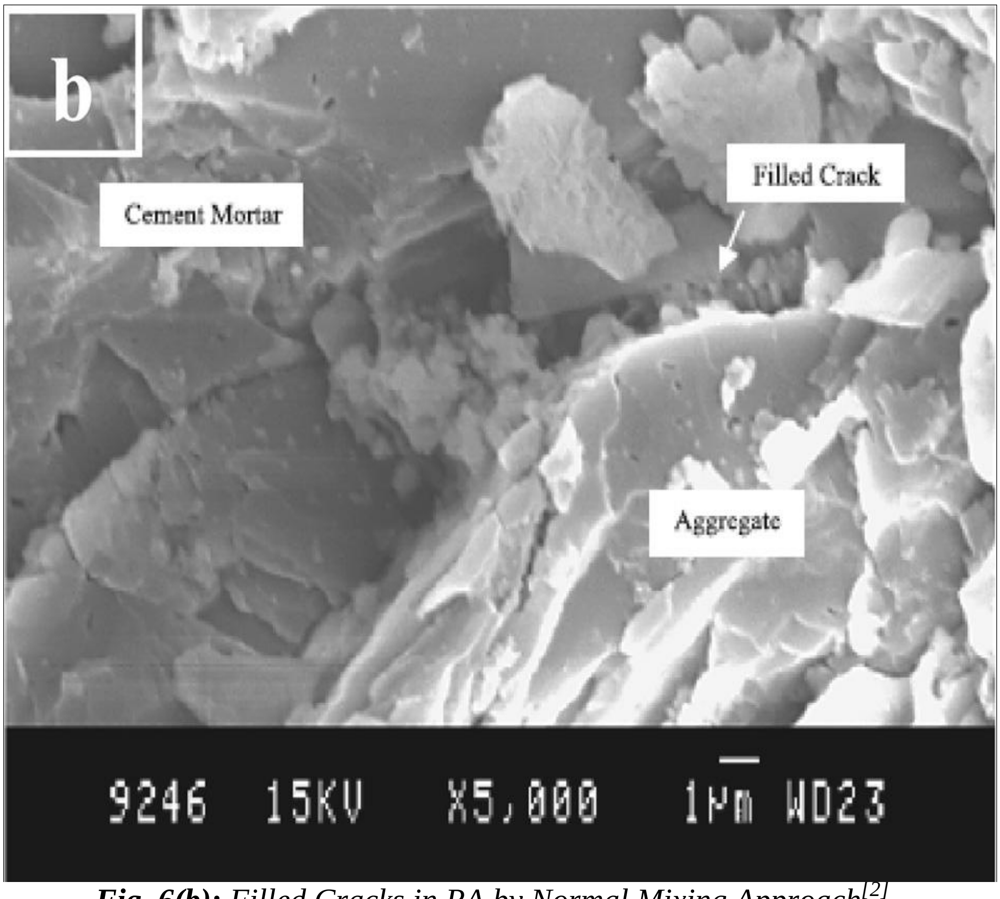

Fig. 6(b): *Filled Cracks in RA by Normal Mixing Approach[2].*

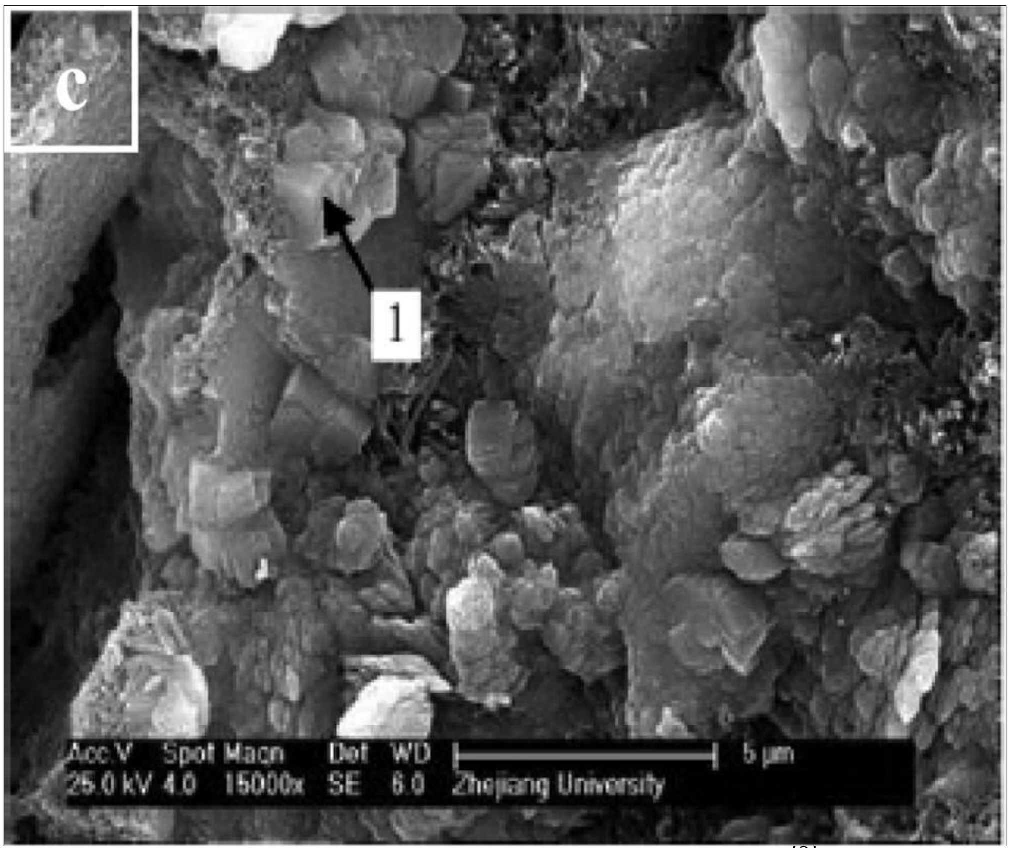

Fig. 6(c): *Without Surface Treatment (in pores)*[2].

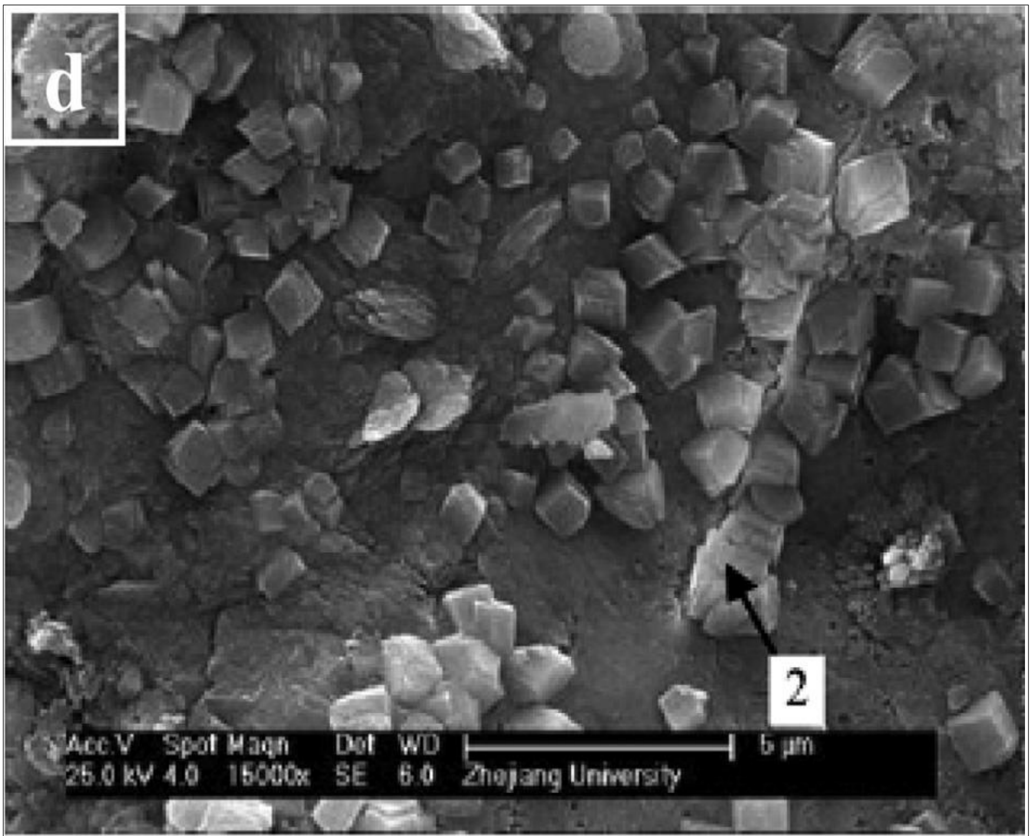

Fig. 6(d): *Without Surface Treatment on surface*[2].

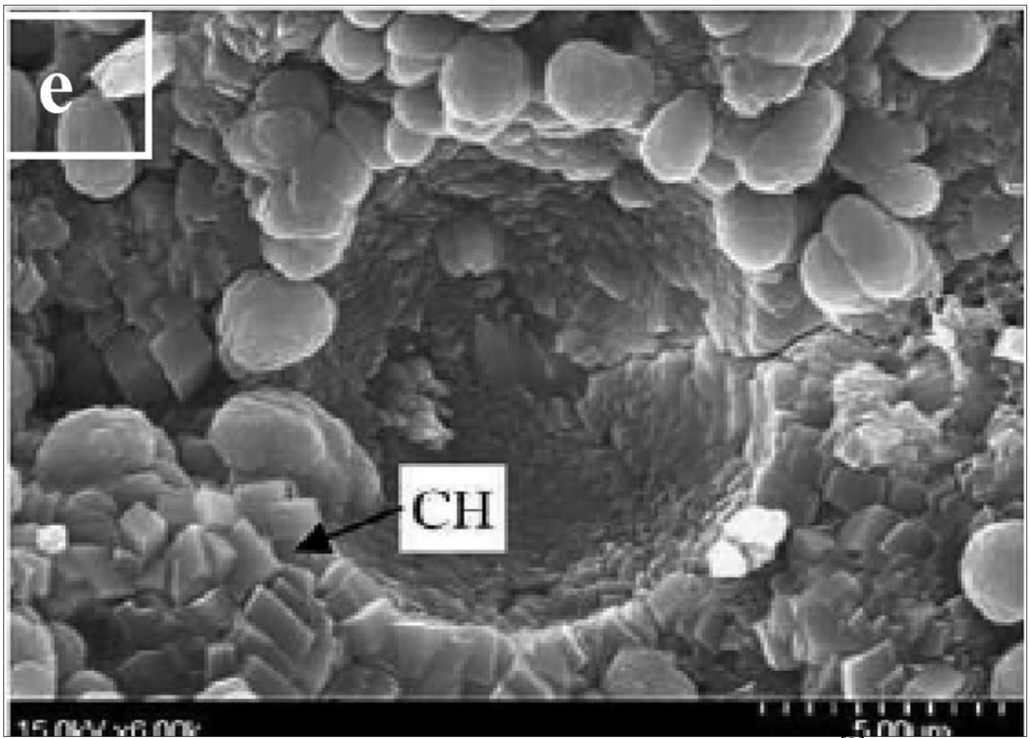

Fig. 6(e): *Surface Microstructure of RA with Fly Ash[2].*

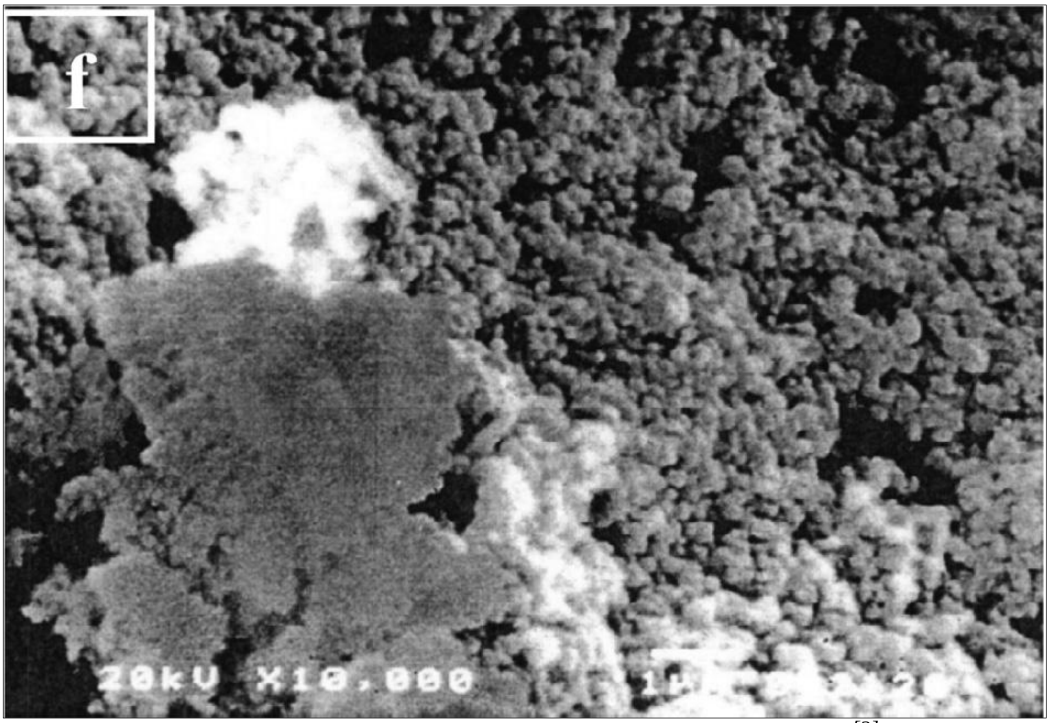

Fig. 6(f): *Surface Treated RA in Silica Fume Solution[2].*

Visualization of Inner Structure of RA and RAC

Monitoring technology is the other advancement in engineering studies to demonstrate the inner structure of materials. Microscopy is evolved from macro-scale observation to meso/micro-scale observation. Scanning electron microscopy (SEM), in this research field, provides convenience to understand what happened in the materials. Hence, many researchers utilized the advancement of monitoring technology to show the structure of RAC as shown in Figure 2 and generally the aggregate-cement zone is demonstrated[29,36–38] as represented in Figure 6 and 7.

Some researchers studied the production of RA in order to investigate RA effect on RAC[27]. Hence, the resultant RA is examined using microscopy and image analysis. According to Nagataki *S. et al.*[27] the research is carried out at three levels of recycling process and when the recycling process is extended up to Level 3 as shown in Figure 8, the particles mostly lose their porosity, crack openings and adhered mortar. Remarkable results as shown by Nagataki S. *et al.*[27] are demonstrated stating that sandstone coarse aggregate has irregularities as voids, and cracks in addition to adhered mortar, is defined using fluorescent microscopy and image analysis, which affects the quality of RA. On the contrary, ITZ of RA is found different from natural aggregate[37] and the micro-structure of RA is enhanced by using mineral admixtures (i.e., fly ash)[29]**.**

According to the utilization of pozzolanic particle with RA in RAC[29], both micro-structure of ITZ and *in-situ* strengthened RA are influenced positively and hence, the durability of RAC is further improved.

As stated above, the secondary C–S–H gel plays a role in improving the structure properties of RA. ITZ of RA is found to be more porous and RA has non-hydrated old cement paste. It can be stated that the low properties of RA and resource of RAC failure through the RA depend on observed ITZ of RA. The research carried out by Erdem S. *et al.*[38] is subjected to determine the influence of the micro-scale local mechanical properties of ITZ and many methods (e.g., digital image analysis, 3D nanotech vertical scanning interferometry, 3D X-ray computed tomography, and SEM coupled with energy dispersive X-ray micro-analysis) are utilized to define the micro-structure and ITZ. In this research, [38] the increased roughness of ITZ may play a vital role in the load-carrying capacity of concrete positively.

Hence, ITZ roughness increasing methods or additions cause positive effects on RAC. For instance, the addition of mineral fills the gaps in ITZ and secondary C–S–H gels forms the structure increasing surface roughness as depicted in Figure 6 (e) and (f). Hence, according to the micro-scale behavior effects on the macro-scale behavior, RAC is influenced by micro-structure of RA.

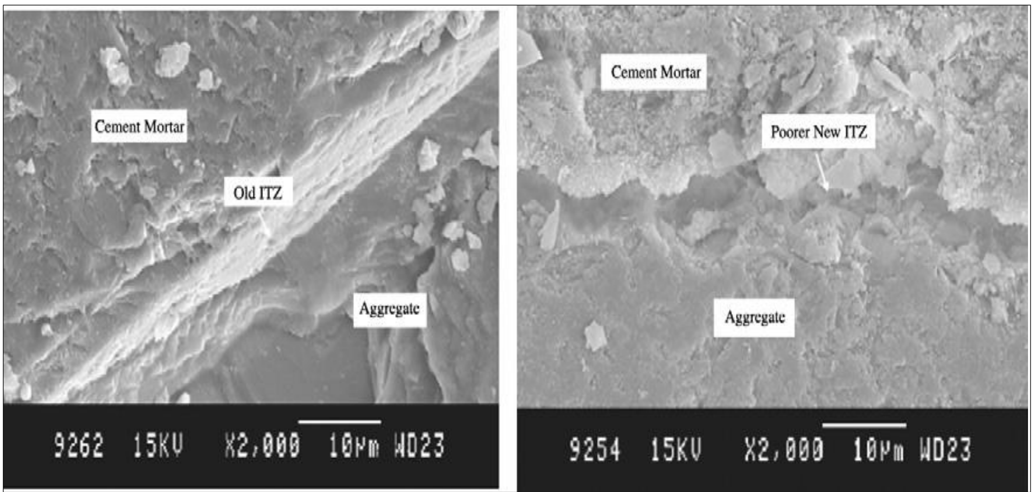

Fig. 7: *The Microstructure Characteristics of ITZs in RAC*[36].

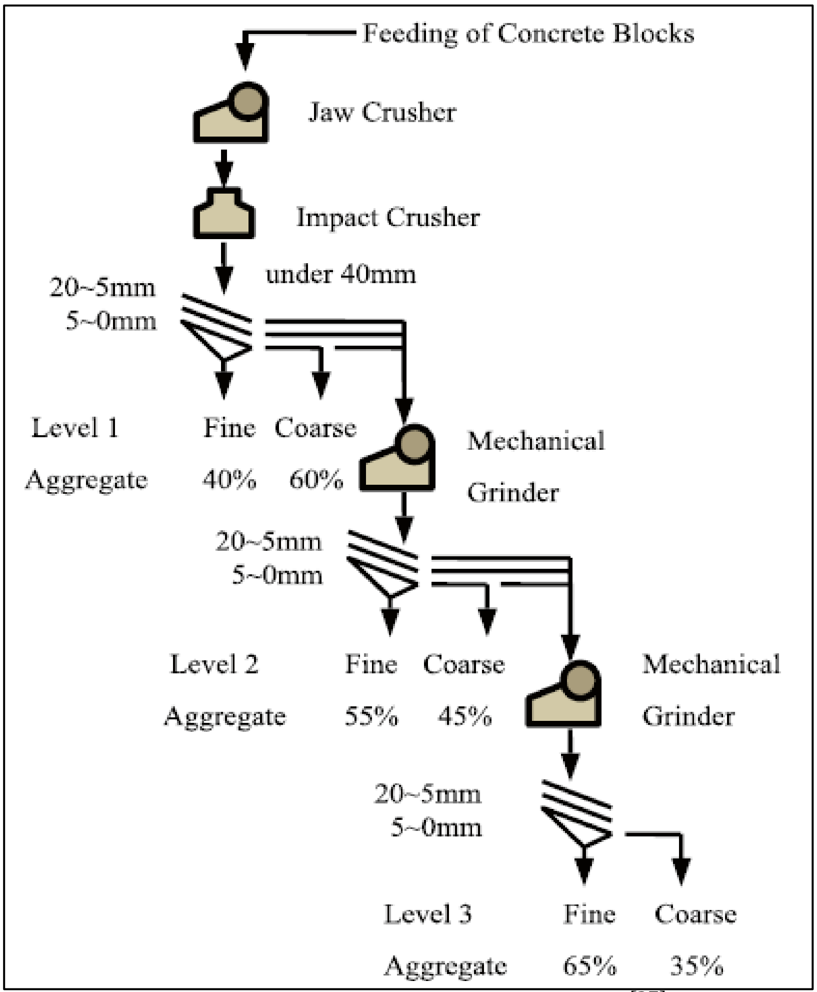

Fig. 8: *Flow of the Recycling Process[27].*

Numerical Works and Computer Modeling Works

In the literature, some researchers utilized both experimental results and/or computer model results to observe the crack behavior of RAC[28,39,40]**.** Hence, Xiao *et al*.[28] set an experimental study and remarkably predicted the failure patterns of RAC under compressive loading. In study conducted by Xiao *et al*.[28]**,** it is observed that the fracture begins around the aggregates as the cracks are formed and propagates along both old and new ITZs and this result was observed for both experimental stage and numerical stage which is represented in Figure 9 and 10. Hence, ITZ have effects on the micro-crack initiation. It is also reported in the study conducted by Xiao *et al*.[28] that with an increment of the properties of the new mortar matrix, the micro-crack localization changes the way from new ITZ through old ITZ. It is emphasized that the significant role in the failure patterns of modeled RAC is played by relative mechanical properties between ITZs and mortar matrices and the mechanical properties of new mortar matrix. In the study conducted by Li W. *et al.*[39]**,** RAC specimens are subjected to compressive load and the behavior using Digital Image Correlation is observed.

While loading, initiation and propagation of cracks are analyzed using produced contour maps of strain and displacement. It is found that the relative strength of coarse aggregate and mortar matrix affects the failure process, and the initiations and propagations of micro-cracks of RAC and NAC are different.

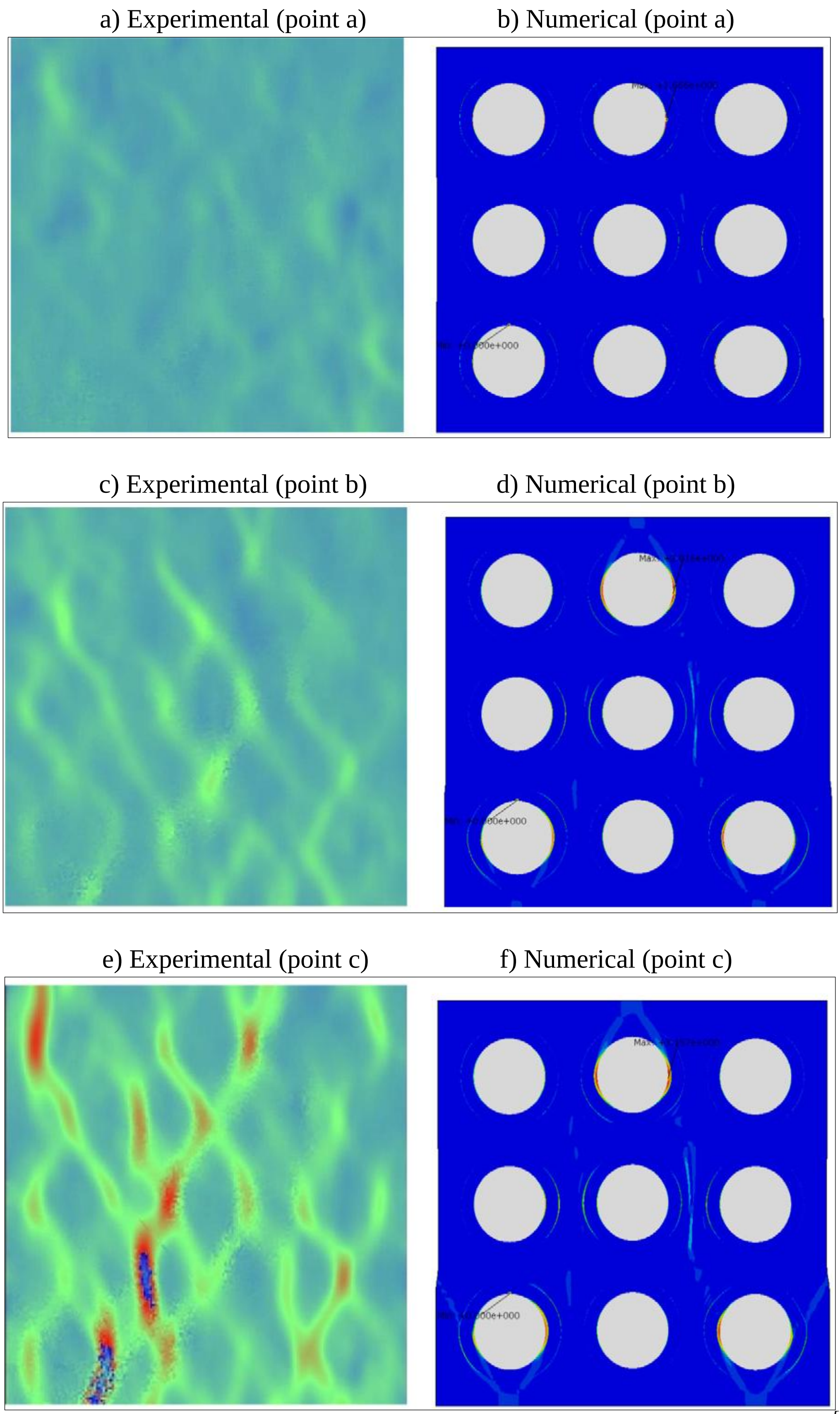

***Fig. 9:** Micro-Scale Crack Development at Different Loading Levels (Simulation)*[28].

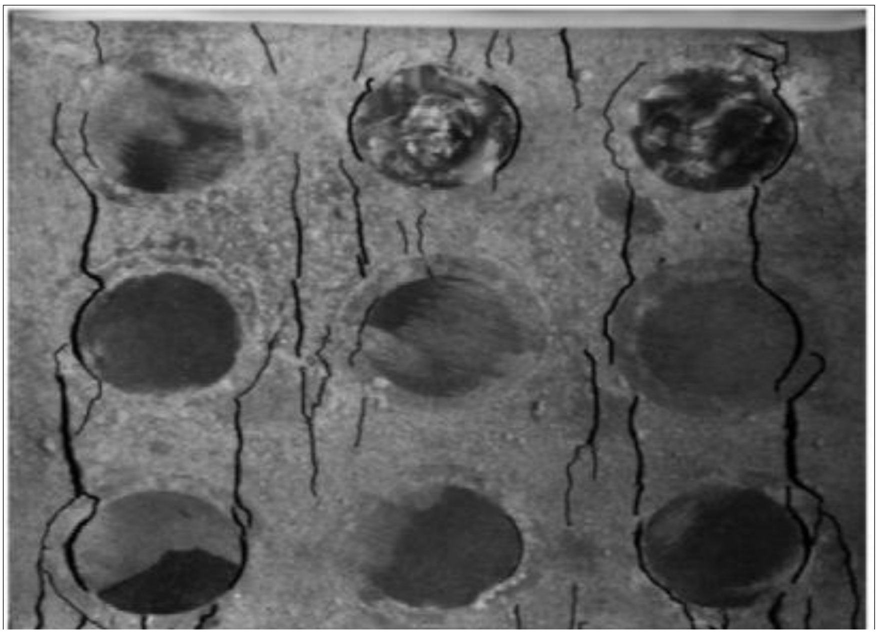

***Fig. 10**: Experimental Study on MRAC under Uniaxial Compression (Experiment)*[28].

Cyclic Loading Effect

The fracture and failure behavior of RAC under cycling loading is very limited in the literature [41,42]. The lower fatigue life of RAC under cyclic bend loading is observed in comparison to NAC[41] as lower properties of RAC (i.e., elasticity modulus, compressive strength) are found by other researchers in comparison to NAC[1]. However, in the studies conducted by Xiao *et al*.[41] the remarkable result is stated that there is no significant difference in RAC and NAC under cyclic compression and bending loadings is observed. At the beginning of the test, to collapse RAC, there are three stages[42]. In the Stage II, the accumulation of damage due to fatigue cycles reaches linear increase in strain and a loss of stiffness is caused by the crack growth[42]. In the Stage III, increasing deformation is observed and the collapse of the concrete is caused by the crack's inter-connections[42]. Hence, the serviceability of engineering structures made up of RAC should be reconsidered if RA is utilized in the concrete.

Due to limited researches, no comment can be impressed to predict the behavior of RAC in this area for future engineering applications. However, it is commonly known that crack propagation is influenced by the cyclic loadings.

Although it is reported[41] that there is no significant difference in the failure characteristics between NAC and RAC under cyclic bending. It is also stated that the progressive development of cracks, while increasing number of loading cycle N, is similar under the conditions of static loading[41], utilizing various concrete materials (i.e., mineral additions) in RAC this area should be enhanced.

CONCLUSIONS AND RECOMMENDATIONS

The present paper aims to review the literature related to the fracture of RAC. Based on the above results, the following main conclusions can be drawn:

1. The failure of RAC occurs at the weakest point, which is RA for RAC and ITZ for NAC. ITZ of RA is found to be more porous and RA has non-hydrated old cement paste. It can be stated that the low properties of RA and resource of RAC failure through the RA depend on observed ITZ of RA.

2. The effect of the mixing methods (i.e., triple mixing method) on the RA which has porous structures, cracks and fissures helps in filling up pores and cracks. This results in an improved ITZ of RA and a denser concrete.
3. Surface coating of RA with mineral additions (i.e., fly ash, silica fume) is an effective method to improve the low properties of RA. Also, the same comments can be said for utilization mineral addition in concrete mixes. Mineral additions provide secondary C–S–H gel to improve the properties of RA and RAC.
4. The numerical and computer models gave similar results to experimental results. Hence, it is a safer way to demonstrate the cracks of materials. The possible crack and crack propagation can be estimated. Modeling of the behavior of RAC can be examined for better understanding and applications.
5. The involvement of monitoring methods (i.e., SEM) has effective results on RAC. Screening of ITZ is convenient to understand what happens in the structure of materials. The methods also provide to produce more effective concrete applications.

Based on the above results, the main recommendations can be summarized as:

1. The fatigue damage is the most important problem for the engineering structures, and micro/meso/macro cracks should be observed by carrying out more researches in future.
2. Long term fracture and failure behavior of RAC and modification of micro-structure and nano-structure of RAC needs to be studied. The nano-scale studies on the structure of RA and RAC (i.e., ITZ) should be done.
3. ITZ of RA is found to be more porous and RA has non-hydrated old cement paste. Hence, more researches needs to be conducted to check the influence of mineral admixtures on the nano-structure of RAC.
4. More researches needs to be conducted on numerical modeling of RAC for better understanding.

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