CHAPTER 5

INFLUENCE OF PROCESSING TECHNIQUE ON RAC

5.1 Introduction

In this chapter, the influence of processing technique on the properties recycled aggregate concrete (RAC) were studied. Normally, the performance of RAC was mainly dependent on the quality of recycled aggregate used. The normal mixing approach (NMA) and four types of recycled aggregates namely: i) PRA(0-RVS), ii) PRA(200RVS), iii) PRA(500RVS) and iv) PRA(700RVS) are used. The M75 grade concrete mix proportion was kept constant throughout the work. Various properties of RAC are studied on each new mix prepared by replacing the virgin coarse aggregate percentage with PRA/RA. The percentage replacement of virgin coarse aggregate with PRA/RA varies from 0 to 100 in steps of 10. Each RAC made with processed recycled aggregates (PRAs) were compared with one another to select the most suitable processed recycled aggregate. The most useful PRA was selected by optimizing the degree of processing. Furthermore, this optimized processed recycled aggregate has been utilized in all two-stage mixing approaches (chapter 6).

In order to optimize the degree of processing, the properties of concrete namely: i) workability (slump), ii) mechanical properties: density, compressive strength, flexural strength, split tensile strength, modulus of elasticity, and ultrasonic pulse velocity (UPV) and iii) durability properties: water absorption, sorptivity, chloride-ion penetration, drying shrinkage and abrasion resistance were examined. Furthermore, scanning electron microscopy (SEM) was also conducted on samples of RAC. The results and discussions are given below.

5.2 Workability

The workability of fresh concrete is expressed as slump value in mm. The slump values of RAC varied within the range of 40 mm (un-processed RA) to 140 mm (processed RA). The slump values are shown in Figure 5.1 and Table B.1 (appendix-B). It can be seen that the slump
values decreased with the increase of PRA content in all types of processed recycled aggregates [i.e., PRA(0-RVS), PRA(200RVS), PRA(500RVS) and PRA(700RVS)]. In all concrete mixes produced in NMA and TSMAs, the value of slump is not less than 70 mm even at 100% replacement level of natural aggregates with PRA(500RVS). This ensures that the RAC has good workability with processed recycled aggregates. The workability is necessary for any fresh concrete, which can be thoroughly mixed to ensure a reasonable uniform distribution of the various constituents of concrete and then successfully compacted into place. Additionally, the fresh concrete must be adequately cohesive to enable such mixing and compaction to be carried out without undue segregation of constituents.

The degree of processing plays a vital role on slump values. In case of higher degree of processing (i.e., Processing of RA with more number of revolutions in Los Angeles Abrasion machine containing steel balls), the old adhesive mortar attached on the periphery of recycled aggregate has been removed much more effectively and the surface become smoother than at a lower degree of processing. Hence, the slump values increased with increasing degree of processing.
Normally, smoother and rounded aggregates give more slump values than angular aggregates [Shetty (2005)]. Furthermore, at any replacement level of VCA with PRA in RAC, the corresponding slump values of PRA (200RVS) have always been higher than that of PRA(0-RVS). The slump values of PRA(500RVS) are higher than that of PRA(200RVS) at any corresponding replacement level. The variation between PRA(700RVS) and PRA (500RVS) is very small when compared with the variation between PRA(0-RVS) and PRA(200RVS). The variation between PRA(500RVS) and PRA(200RVS) is also more. Therefore, PRA(500RVS) is a suitable one to produce high-strength RAC with a slump of 80± 40 mm. Thus the processing of RA with 500 revolutions treatment (i.e., degree of processing) is enough to produce high quality of RA.

5.3 Mechanical properties

The mechanical properties of RAC namely: i) density, ii) strengths (compressive, flexural and split tensile strength), iii) modulus of elasticity and iv) ultra sonic pulse velocity (UPV) have been studied and their results and discussion are given below.

i) Density:

The variations in densities of recycled aggregate concrete (RAC) made with various processed recycled aggregates [PRA (0-RVS), PRA (200RVS), PRA (500RVS) and PRA (700RVS)] at 28 and 90 days are shown in Figures 5.2 and 5.3. The density measurements of RAC are the average of three samples tested and reported in Table B.2 (appendix-B). In all the cases of processed recycled aggregates, the density values have decreased linearly as the percentage of PRA increased. This might be attributed to the lower bulk density of PRA than virgin coarse aggregate (VCA). The other possible reason for lower density may be the presence of loose particles, adherent cement mortar, pores, cavities, voids, fissures, and cracks in PRA. The unfilled pores, cavities, cracks etc cause the poor strength and lower densities as well in the resultant concrete (RAC). Generally, the internal cracks of RA may form at the time of production stage.
Figure 5.2: Density of concrete using NMA at 28 days

Figure 5.3: Density of concrete using NMA at 90 days
The degree of processing played an important role. The densities of recycled aggregate concrete made with PRA of higher degree processing has always shown better results than that of lower degree processing at any corresponding replacement level. A considerable improvement is observed in density values of concrete made with processed RA than un-processed aggregate cases. Therefore, it is better to use RA after processing to produce dense concrete. The densities of PRA(500RVS) have shown higher values than PRA(200RVS). Similarly the densities of PRA(200RVS) also have shown higher values than PRA(0-RVS) results at any corresponding replacement level. The PRA(700RVS) show higher values of density than PRA(500RVS). However, the difference between PRA(700RVS) and PRA(500RVS) is very marginal. Therefore, the suitable degree processing is 500 revolutions only.

ii ) Strengths (compressive, flexural and split tensile)

The compressive, flexural and split tensile strengths of concrete were measured at the ages of 7, 28, 56, 90 and 180 days. Every presented data is an average of three measurements made on cubes, beams and cylinders respectively. The compressive strength results of concrete made with all types of processed recycled aggregates are shown in Figures 5.4 to 5.8. Similarly, the Flexural strength results of concrete made with all types of processed recycled aggregates are shown in Figures 5.10 to 5.14. In addition, the split tensile strength results of concrete made with all types of processed recycled aggregates are shown in Figures 5.16 to 5.20.

The corresponding numerical values of compressive, flexural and split tensile strengths are shown in Tables B.3, B.4 and B.5 (appendix-B) respectively. Moreover, the influences of processing (expressed in percentage improvements) of PRAs on compressive, flexural and split tensile strengths in comparison with un-processed recycled aggregate are shown in Figures 5.9, 5.15 and 5.21 respectively.

The detailed results and discussions of strengths (compressive, flexural and split tensile) are given after figures.
Figure 5.4: Compressive strength of concrete using NMA at 7 days

Figure 5.5: Compressive strength of concrete using NMA at 28 days
Figure 5.6: Compressive strength of concrete using NMA at 56 days

Figure 5.7: Compressive strength of concrete using NMA at 90 days
Figure 5.8: Compressive strength of concrete using NMA at 180 days
Figure 5.9: Influence of processing on compressive strength in comparison with un-processed recycled aggregate [PRA(0-RVS)]
Figure 5.10: Flexural strength of concrete using NMA at 7 days

Figure 5.11: Flexural strength of concrete using NMA at 28 days
Figure 5.12: Flexural strength of concrete using NMA at 56 days

Figure 5.13: Flexural strength of concrete using NMA at 90 days
Figure 5.14: Flexural strength of concrete using NMA at 180 days
Figure 5.15: Influence of processing on flexural strength in comparison with un-processed recycled aggregate [PRA (0-RVS)]
Figure 5.16: Split tensile strength of concrete using NMA at 7 days

Figure 5.17: Split tensile strength of concrete using NMA at 28 days
Figure 5.18: Split tensile strength of concrete using NMA at 56 days

Figure 5.19: Split tensile strength of concrete using NMA at 90 days
Figure 5.20: Split tensile strength of concrete using NMA at 180 days
Figure 5.21: Influence of processing on split tensile strength in comparison with un-processed recycled aggregate [PRA (0-RVS)]
Based on the experimental results shown in Figures 5.4 to 5.21 it can be concluded that the trend of strength results (compressive, flexural and split tensile) is almost same. In all types of concrete mixes made with processed recycled aggregates [PRA(0-RVS), PRA(200RVS), PRA(500RVS), PRA(700RVS)] a gradual decrease in strength was found with the increase of PRA content. Similar trend of results were observed in the studies of other researchers [Didier and Kong (2012)]. A clear enhancement in strengths was also observed with the degree of processing in all types of concrete mixes made with processed recycled aggregates. The higher degree of processing of RA has always shown improved/better results of strengths.

The results of strengths (compressive, flexural and split tensile) were decreased gradually from PRA(700RVS) to PRA(0-RVS) at any corresponding replacement level of VCA with PRAs. From the experimental results it is concluded that, the processed recycled aggregate is better than un-processed recycled aggregate to produce high-strength concrete. Because lot of improvements in results was found in case of all processed recycled aggregates than un-processed RA. Similar types of conclusions were drawn by other researchers [Shima et al. (2005), Wan et al. (2005), Tam et al. (2007), Dhir and Paine (2010), Jishen Qiu et al.(2014)].

The strength (compressive, flexural and split tensile) of concrete is mostly dependent on the strength of the mortar, strength of aggregate and the interfacial transition zone [Wengui et al. (2012), Lee and Choi (2013)]. Generally, the strength of aggregates may be higher than that of mortar. Hence, the bonding between aggregate and mortar is an important parameter to assess strength. The interface between aggregate and mortar is called interfacial transition zone (ITZ). This ITZ is the weakest area through which failure generally takes place[ Neville (2009), Kou et al. (2008)]. The ITZ plays an important role in all mechanical and durability properties as well [Deyu Kong et al. (2010), Kou and Poon (2012)]. The influence of ITZ is very important in case of concrete made with RA. Because the RA always contains some portion of adherent cement mortar and loose particles on its surface. Therefore, the bonding between RA and new mortar may not be that much stronger as in case of concrete made with natural aggregates.

The quality of RA plays a vital role in high-strength recycled aggregate concrete. The quality of un-processed RA may be very poor in majority of the cases due to the presence of loose particles, cracks, pores, fissures, and adherent mortar. The thickness of old adhesive mortar is very high in case of PRA(0-RVS). Because of processing, the thickness and quantity of adhered cement mortar is very small in case of PRA(200RVS), PRA(500RVS) and
PRA(700RVS). Therefore, the ITZ between aggregate and mortar may be very narrow in case of PRA(200RVS), PRA(500RVS) and PRA(700RVS) than PRA(0-RVS), which finally leads to better mechanical properties. In the present study, all the processed recycled aggregates have shown higher strengths (compressive, flexural and split tensile) than un-processed recycled aggregates because of processing effect.

From the experimental results, PRA(700RVS) has shown the best results than any other type of aggregates because of the higher degree of processing. Similarly, the test results of PRA(500RVS) have always shown better results than PRA(200RVS). In the same way, the test results of PRA(200RVS) have always shown improved results than PRA(0-RVS). Even though, the strength results of PRA(700RVS) were better than PRA(500RVS), but the improvement was very marginal. From the Tables of results (compressive, flexural and Split) it is evident that, the improvement (expressed in percentage) of PRA(200RVS) over PRA(0-RVS) is more. Similarly, the improvement (expressed in percentage) of PRA(500RVS) over PRA(200RVS) is also more. But the improvement (expressed in percentage) of PRA(700RVS) over PRA(500RVS) is very less. Hence, it was better to use 500 revolutions treatment/processing as this will reduce the energy demand to achieve economy also.

On the basis of experimental results, even though all the strength results were decreasing with the increase in PRA content, the replacement level of virgin coarse aggregate with PRA(500RVS) up to 50 percent was quite acceptable in case of high-strength mixes. It was interesting to note that, the flexural and split tensile strength results also follow the similar trends of compressive strength in all types of processed recycled aggregates.

iii ) Modulus of Elasticity

From the results, the modulus of elasticity has decreased with the increase of PRA content. This trend was observed just because of the adherent mortar, pores and cavities present in PRAs. The higher degree of PRAs have shown better results than unprocessed RA. In all types of PRAs, a clear enhancement is observed in the values of modulus of elasticity from 28 days to 90 days. The modulus of elasticity of RAC at 28 and 90 days are shown in Figures 5.22 and 5.23 respectively. The corresponding numerical values of modulus of elasticity are given in Table B.6 (appendix-B).
Figure 5.22: Modulus of elasticity of concrete using NMA at 28 days

Figure 5.23: Modulus of elasticity of concrete using NMA at 90 days
At the same replacement level of PRA, the higher degree of processing [PRA(700RVS) and PRA(500RVS)] has shown improved results than PRA(200RVS). Good improvement was also found in processed recycled aggregates PRA(200RVS) when compared with un-processed recycled aggregate [PRA(0-RVS)] at any corresponding level of replacement. However, the ideal degree of processing for recycled aggregate was 500 revolutions only because, the improvement (%) in the experimental results of PRA(700RVS) was not much when compared with PRA(500 RVS), whereas the same improvement (%) was considerably very high in case of PRA(500RVS) when compared with PRA(200RVS). Therefore, based on the experimental results, it was always better to use processed recycled aggregate than un-processed recycled aggregate for the production of high strength concrete.

iv) Ultrasonic pulse velocity (UPV)

The ultrasonic pulse velocity (UPV) of RAC at 28 and 90 days are shown in Figures 5.24 and 5.25 respectively. The corresponding numerical values of results are shown in Table B.7 (appendix-B). In all cases of RAC made with processed recycled aggregates [PRA(700RVS), PRA(500RVS), PRA(200RVS) and PRA(0-RVS)] the UPV values decreased linearly with the increase of PRA content, due to lower density of recycled aggregate concrete. The adherent mortar still present on the surface of PRA is the main reason for this trend. A small portion of adherent cement mortar was still found in PRAs after processing. The quantity of adherent mortar increased with increasing dosages of RA. Therefore at higher dosages of PRA, the UPV values of RAC has decreased.

Higher density of concrete always shows higher values of UPV. Because of adherent cement mortar and loose particles, the recycled aggregate has shown lower bulk density, which finally leads to lower density and UPV values as well. Higher the PRA content, higher is the risk always. From 28 days to 90 days the results were improved in all types of PRAs. On the other hand the improvement in UPV values are very high in case of PRA(200RVS) when compared with PRA(0-RVS). Similarly a good improvement in test results was found in case of PRA(500RVS) when compared with PRA(200RVS).
The higher degree of processing of RA has shown improved results than lower degree of processing. In view of energy, time saving and economy point of view, the PRA(500RVS) is the suitable PRA, because the improvement in UPV values was insignificant in PRA(700RVS) when compared with PRA(500RVS).
5.4 Durability properties

The durability properties of RAC namely: i) water absorption, ii) sorptivity, iii) chloride-ion penetration (RCPT), iv) drying shrinkage and v) abrasion resistance are studied. The results and discussions are given below.

i) Water absorption

The adherent cement mortar, cavities, pores, voids and cracks and fissures are the major reasons for high water absorption and high porosity in recycled aggregate concrete [Poon et al. (2004)]. The porosity and water absorption of recycled aggregate concrete was significantly greater than that of the natural aggregate concrete. The porosity and the pore size distribution are the most important characteristics of the pore system of concrete which influence the ingress of foreign substances to the interior of concrete. The durability properties mainly dependent on the pore system of concrete [Evangelista and Brito (2010), Faiz Uddin and Nguyen (2013)].

![Water absorption of concrete using NMA at 28 days](image)

**Figure 5.26:** Water absorption of concrete using NMA at 28 days
The water absorption capacity of all the concrete mixes made with PRA(0-RVS), PRA(200RVS), PRA(500RVS), PRA(700RVS) has linearly increased while the PRA content was increased. Similar trend of results were observed in the studies of other researchers [Levy Salomon and Helene (2004), Kartini et al. (2010)]. It is well known that the water absorption of concrete below 3% considered as low permeable and good durability [BS EN 1881-122]. The PRA(0-RVS) contains a thick layer of adhesive mortar around the periphery of RA. This might be the main reason for high porosity in concrete, while the RA percentage was increased. The adherent mortar contains lot of cavities, pores and cracks [Kou and Poon (2012)]. The water absorption results of concrete made with un-processed recycled aggregate PRA(0-RVS) were always more than all other concrete mixes made with other processed recycled aggregate viz: PRA(200RVS), PRA(500RVS), and PRA(700RVS). The water absorption results of PRA(700RVS) were slightly less than the PRA(500RVS) results at any corresponding replacement level of VCA with PRA. This has happened just because of the further reduction in thickness of adhesive mortar with 700 revolutions treatment. The water absorption results of PRA(500RVS) was less than PRA(200 RVS) results while the water absorption results of PRA(200RVS) was less than PRA(0-RVS) results. Additionally, the difference in water absorption results of PRA(500RVS) and PRA(200RVS) was considerably more. Similarly the difference in results between PRA(200RVS) and PRA(0-RVS) was also more. The difference in the results of water absorption was very small in cases of PRA(500RVS) and PRA(700RVS).

After processing, the old adherent cement mortar and loose particles are removed considerably and the mortar made with sand, cement and silica fume entered into the weak areas of adhesive mortar, cavities, pores, and voids of PRA and finally made the concrete very dense and water tight. Even though the 700 revolution treatment has shown slightly better results than 500 revolutions treatment, the 500 revolutions treatment of RA was enough to produce high quality RA. This may save energy, time and money. From Figure 5.26, it was evident that the water absorption values increased proportionately with RA content in all types of processed recycled aggregates. These findings were consistent with those reported previously [Kartini et al. (2010), Liam Butler et al. (2014), Gonzalez and Etxeberria et al. (2014)]. The water absorption capacities in percentage for recycled aggregate concrete made with processed recycled aggregates [PRA(0-RVS), PRA(200RVS), PRA(500RVS), PRA(700RVS)] are shown in Figure 5.26 and Table B.8( appendix-B).
ii) Sorptivity

The sorptivity results of recycled aggregate concrete made with processed recycled aggregates for 28 days and 90 days are shown in Figures 5.27, 5.28 and Table B.9 (appendix-B). The sorptivity values in all concrete mixes made with PRA [PRA(0-RVS), PRA(200RVS), PRA(500RVS), PRA(700RVS)] are increasing with increase in PRA content. Similar results were also obtained in the studies of others [Suresh et al. (2009), Kartini et al. (2010)]. This happened because of porosity of concrete due to the old adhesive mortar still left after processing around the periphery of PRA.

![Sorptivity Graph](image)

**Figure 5.27:** Sorptivity of concrete using NMA at 28 days
Figure 5.28: Sorptivity of concrete using NMA at 90 days

Inadequate concrete mixing time also creates large pores [Sallehan and Mahyuddin (2013)]. The other reason for higher sorptivity is because of loose particles, cavities, pores, cracks and fissures etc in the recycled aggregate [Deyu Kong et al.(2010), Patrick and Durham (2012)]. In all cases the sorptivity values of 90 days are lower than the values of 28 days at any corresponding replacement level of virgin coarse aggregate. The sorptivity values were decreased with the increase in degree of processing. These results were comparable to results of other researchers [Limbachiya et al. (2000)] who have applied the RA in high-strength concrete.

The sorptivity decreased from PRA(0-RVS) to PRA(700RVS) because of increase in the degree of processing. The sorptivity results of PRA(200RVS) was less than PRA(0-RVS). The difference in sorptivity results between PRA(200RVS) and PRA(0-RVS) was considerably more. The sorptivity results of PRA(500RVS) was less than PRA(200RVS). Even though the sorptivity results of PRA(700RVS) was less than PRA(500RVS) but the difference in results was very small. Therefore, based on the experimental data, the PRA treated with 500 revolutions was enough to produce high-strength concrete and this may save money as well as energy.
iii) Chloride-ion permeability (RCPT)

The RCPT (Rapid Chloride Permeability Test) results according to ASTM C1202-12, of concrete mixes at 28 days and 90 days are shown in Figures 5.29, 5.30 and Table B.10 (appendix-B). It is seen that, the resistance to chloride–ion permeability of concrete mixes decreased with an increase in PRA percentage in all concrete mixes. In other way, the chloride-ion penetration (total charge passed expressed in coulombs) increases with the increase of PRA dosage in all cases [PRA(0-RVS), PRA(200RVS), PRA(500RVS) and PRA(700RVS)]. This has happened mainly because of adherent cement mortar still present on the periphery of recycled aggregate after processing also. The RCPT set up is shown in Figure 5.31. In addition, the values given in Table 5.1 are used to assess the chloride-ion permeability in concrete.

![Graph showing RCPT values (Coulombs) of RAC using NMA at 28 days](image-url)

**Figure 5.29:** RCPT values (Coulombs) of RAC using NMA at 28 days
**Figure 5.30:** RCPT values (Coulombs) of concrete using NMA at 90days

**Table 5.1:** Level of chloride-ion penetrability based on RCPT value [ASTM C 1202-12]

<table>
<thead>
<tr>
<th>RCPT value (or) Charge passed (coulombs)</th>
<th>Chloride-ion Penetrability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4000</td>
<td>High</td>
</tr>
<tr>
<td>2000 - 4000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1000 - 2000</td>
<td>Low</td>
</tr>
<tr>
<td>100 - 1000</td>
<td>Very low</td>
</tr>
<tr>
<td>&lt; 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
Figure 5.31: Rapid chloride permeability test (RCPT) setup

The R.C.P.T. values (coulombs) of concrete made with PRA(700RVS), PRA(500RVS) and PRA(200RVS) were less than the results of PRA(0-RVS) at any corresponding replacement level of natural aggregates. This happened due to the reduction of adherent mortar, low porosity and higher density of RAC. The R.C.P.T. values of 90 days are lower than the values of 28 days at any dosage of PRA. The durability of the concrete can be strongly affected by permeability [Suresh et al. (2009)]. In case of PRA(700RVS), PRA(500RVS) and PRA (200RVS), the thickness of old adhesive cement mortar is reduced considerably such that the silica fume and cement slurry forms a thin impermeable cover around the periphery of recycled aggregate after filling the pores, cavities, fissures and cracks which resists the chloride ion penetration. From test results, the difference of R.C.P.T. values between PRA(700RVS) and PRA(500RVS) was very small, whereas the same difference
of results between PRA(200RVS) and PRA(0-RVS) was considerably high. Hence PRA(500RVS) was more preferable processed recycled aggregate than all other types of processed aggregates to produce higher grade concrete mixes. This was more beneficial to achieve economy. All the processed recycled aggregates have shown better results than unprocessed recycled aggregate [PRA(0-RVS)].

v) Drying shrinkage

Most of the shrinkage has occurred during the first 7 days and then slow down [Jianzhuang and Falkner (2007)]. The drying shrinkage values of processed recycled aggregate were less than unprocessed recycled aggregate values at any level of PRA replacement. The drying shrinkage values in all concrete mixes made with PRA [PRA(0-RVS), PRA(200RVS), PRA(500RVS) and PRA(700RVS)] were increased linearly with increase of PRA content. This has happened because of old adhesive mortar present around the periphery of PRA after processing, which actually contributed to an increase in volume of paste (old+ new), thus increasing the drying shrinkage.

![Figure 5.32: Drying shrinkage of concrete using NMA at 112 days](image)

The drying shrinkage of PRA(700RVS) and PRA(500RVS) have shown better results at any replacement level of PRA, when compared with PRA(200RVS) and un-processed recycled aggregate [PRA(0-RVS)]. The drying shrinkage values of PRA(200RVS) was less than
PRA(0-RVS) at any replacement level. The difference in test results between PRA(200RVS) and PRA(0-RVS) was considerably high. Similarly, the difference in test results between PRA(500RVS) and PRA(200RVS) was also high. But, the difference in test results between PRA(700RVS) and PRA(500RVS) was very small. Hence, 500 revolutions treatment of RA was adequate treatment to produce high strength concrete to achieve economy and energy saving. The same behavior confirms previous reports by other authors [Sabbir et al. (1998), Tam et al. (2005)]. The experimental results of drying shrinkage of the all mixes at the drying period of 112 days are shown in Figure 5.32 and Table B-11 (appendix-B).

vi) Abrasion resistance

The abrasion loss of concrete is reported as the average of the results obtained for the 12 surfaces As per IS:9284-1997 (i.e., 4 surfaces each of 3 cubes), to the nearest 0.01 gram and expressed as percent loss. The abrasion loss of concrete increased with increased PRA content in all concrete mixes made with PRA(0-RVS), PRA(200RVS), PRA(500RVS), and PRA(700RVS). The abrasion loss has decreased in processed recycled aggregates [PRA(700RVS), PRA(500RVS) and PRA(200RVS)] than un-processed recycled aggregates [PRA(0-RVS)] for any corresponding level of VCA replacement. The better results were found in PRA(700RVS) and PRA(500RVS). The test results are shown in Figure 5.33 and Table B-12 (appendix-B).

![Figure 5.33](image)

**Figure 5.33:** Abrasion resistance of concrete using NMA at 28 days
Based on the experimental results, the PRA(200RVS) results were better than PRA(0-RVS) results and the PRA(500RVS) results were better than PRA(200RVS) results for any corresponding replacement level of virgin coarse aggregate. From the experimental results, the PRA(500RVS) was suitable aggregate to produce durable concrete than un-processed aggregates by considering economy point of view, because there was not much difference in between PRA(700RVS) and PRA(500RVS).

5.5 Scanning electron microscopy (SEM)

The scanning electron microscopy has been conducted on the samples of RAC produced by using various processed recycled aggregates and natural aggregates. The set up of LEO 435 variable pressure scanning electron microscope (UK made) is shown in Figure 5.4. Moreover, Figures 5.35 to 5.38 shows the SEM photographs of concrete made with PRAs and natural aggregates. The interfacial transition zones between aggregate phase and mortar phase have been shown very clearly in the following photographs. The thickness of ITZ in case of PRAs/TSMAs has been given in Table C.20 (appendix- C).

![Figure 5.34: Scanning Electron Microscopy on samples of RAC](image)
Figure 5.35: SEM photograph of RAC using PRA(0-RVS) in NMA

Figure 5.36: SEM photograph of RAC using PRA(200RVS) in NMA
Figure 5.37: SEM photograph of RAC using PRA(500RVS) in NMA

Figure 5.38: SEM photograph of RAC using PRA(700RVS) in NMA
Influence of processing technique on ITZ

The ITZ between aggregate and mortar phase plays an important key role in concrete [Neville (2009)]. The interfacial transition zone (ITZ) is the weakest component in concrete. Generally the failure takes place through ITZ [Otsuki et al. (2003)]. Incase of VCA the aggregate has attached to the cement mortar strongly. But in case of recycled aggregate, two ITZs are present one between RA & new paste (new ITZ) and another one between the old aggregate & old adhesive mortar of recycled aggregate [Wengui et al. (2012)]. The adhesive cement mortar attached to RA contains many minute pores and cracks that finally affects the mechanical and durability properties of RAC[Crentsil et al. (2001), Xiao et al. (2004), Kou and Poon (2012)].

Based on the experimental results, lot of improvement was found in case of RAC made with PRAs. The other main reasons for improved properties of recycled aggregate concrete are: i) after processing the cement slurry can enter into the cavities, pores, fissures, voids and cracks of RA very easily at the time of mixing, ii) better bonding may be achieved between clean surface of recycled aggregate and cement paste due to the removal of adhesive mortar
after processing and iii) due to the pozzolanic action of silica fume. Silica fume enters into the pores, cavities, fissures, cracks, voids and weak areas of recycled aggregate and finally acts as reinforcing filler. The silica fume and cement strengthen the ITZ [Mukharjee and Kumar (2014)]. Therefore, the concrete made with processed recycled aggregates has shown better results than un-processed recycled aggregate in all properties. The improvement of RAC has been observed in case of all SEM photographs given above. The ITZ of RAC is strengthened with processing effect of RA.

5.6 Selection of most suitable processed recycled aggregate (PRA)

Based on experimental data, the thickness of old cement mortar around the periphery was reduced and cavities, pores, fissures cracks and voids of PRA are filled with cement mortar in case of PRA(200RVS). Therefore, the results of PRA(200RVS) are improved when compared with un-processed aggregate [PRA(0-RVS)]. Similarly the PRA(500RVS) also has shown better results than PRA(200RVS). Because of the higher degree of processing, the PRA(500RVS) and PRA(700RVS) almost acts like VCA and shows enhanced properties than PRA(200RVS). In case of RAC made with PRA(0-RVS), the ITZ is very broad in thickness. The thickness of ITZ is medium in case of RAC made with PRA(200RVS). Where as the thickness of ITZ is very narrow/thin in case of RAC made with PRA(500RVS) and PRA(700RVS). The thin ITZ has been observed due to the removal of loose particles and adherant material from the surface of PRA(500RVS) and PRA(700RVS).

Even though, a slight improvement was found in all test results of PRA(700RVS) than PRA(500RVS), it is concluded that, the optimum of number of Los Angeles abrasion machine revolutions for processing of recycled aggregate was 500 only because of, economy and energy saving. Based on experimental results, the PRA(500RVS) was best and suitable processed recycled aggregate when compared with all other processed recycled aggregates [PRA(0-RVS), PRA(200RVS) and PRA(700RVS)] used in this work. The processed recycled aggregate after 500 revolutions treatment [i.e., PRA(500RVS)] was suitable one to produce high-strength concrete and to utilize the recycled aggregate in high dosages for sustainable constructions.
5.7 Conclusions

Based on the experimental study (chapter-5) the following conclusions were drawn:

1. High-strength concrete (a minimum of 60MPa) can be produced even at 100% replacement level of natural aggregates by using PRA(500RVS). However, at that 100% replacement level, the 28-day compressive strength decreased by about 27% of the concrete made with natural aggregates, whereas the same reduction in strength was about 60% in case of unprocessed RA. Thus, it is clearly concluded that recycled aggregate (RA) can be used in high-strength concrete provided that proper processing is done.

2. In the normal mixing approach, better results of RAC were observed while the numbers of revolutions were increased in the processing technique. In other words, the results were improved with the degree of processing of RA.

3. Even though the results of 700 revolutions treatment were better than those of 500 revolutions treatment, the improvement was only marginal. Thus, it was suggested to adopt 500 revolutions treatment as this will reduce the energy, time and cost as well. Therefore, the PRA(500RVS) has been selected as the most appropriate one to make high-strength concrete.

4. All the examined properties (slump, density, U.P.V and strength, water absorption, sorptivity, RCPT, drying shrinkage and abrasion resistance) of RAC made with PRA showed improvement in comparison to those of RAC made with un-processed RA.

5. The substitution of PRA(500RVS) up to 50% has been found to produce a high-strength concrete (a minimum of 70MPa). At this replacement level, the loss of 28-day compressive strength is about 14% only compared to 46% in the case of un-processed RA.