2.1 RECYCLED CONCRETE AGGREGATE

2.1.1 General

In recent years certain countries have considered the reutilisation of construction and demolition waste as a new construction material as being one of the main objectives with respect to sustainable construction activities.

The literature review presents the current state of knowledge and examples of successful uses of alternative materials in concrete technology, and in particular the use of Recycled Concrete (RC) aggregate as a coarse aggregate fraction in non-structural and structural concrete. Many researchers have dedicated their work to describe the properties of these kinds of aggregate, the minimum requirements for their utilisation in concrete and the properties of concretes made with recycle aggregates. It also presents a review of available literature on physical, mechanical and durability properties of RC aggregates, and mechanical, durability and structural properties of RCA concrete. However, minor attention has been paid to the structural behavior recycled aggregate concrete slabs. This thesis focuses on recycling of concrete waste as an aggregate in structural concrete in flexure and punching shear.

2.1.2 Constituent Materials in Concrete

Modern concrete is a sophisticated compositied material which is constantly undergoing improvements and modifications. However, the basic constituents of conventional Ordinary Portland Cement (OPC) concrete such as fine and coarse
aggregate, cement and water remain same. There are other materials such as chemical admixtures including superplasticisers, water reducers and air-entrainers that can be used to modify the characteristics of OPC concrete. There is also an increase in the use of Pozzolanic materials like fly ash, metakoline, granulated blast-furnace slag and silica fume. Over the last few decades, the uses of various alternative fine and coarse aggregates in the production of concrete have been investigated, including the use of RC aggregates.

2.1.3 Concrete Waste and Concrete Recycling

Concrete waste, which falls into the Construction and Demolition (C & D) waste category, is generated when creation of new, or modifications to existing urban infrastructure such as transport systems, communication networks and buildings are made. With the increased urbanisation of the world's growing population there is also an increase in C & D waste generation. This prompts a realisation that built-in urban infrastructure along with C & D waste contains a large stock of materials, and that efficient management of concrete, steel, bricks, their waste, is necessary to sustain the future growth and increased demand for construction materials.

In developed countries there is an increased societal demand on government agencies and industries to search for alternative materials and reduce waste to achieve ecologically sustainable development, resulted in an increased rate of recycling, and reuse of concrete waste. It seems that there is a common understanding and consensus that depletion of natural resources is a real threat, landfill space is becoming scarce, and the waste disposal causes significant environmental and social impact. There is
also a general consensus that recycled C & D waste including RC aggregates can be used for construction purposes.

The main source of raw material for recycling of concrete waste comes from demolition of concrete structures. The quality and purity of the raw material affect the quality of recycling products and ultimately commercial acceptance of concrete recycling products. The process of manufacturing concrete recycling products is relatively simple. To produce high quality concrete recycling products that satisfy commercial and technical specifications, it is crucial to segregate concrete waste at source eliminating any low and high density and friable contaminants. Recycling process and plant setup depends on desired grading and quality of the final product. In situations when crushed concrete waste is to be used as fill material, the use of a mobile crusher is usually sufficient. However, when crushed concrete waste is used to produce RC aggregates for road sub-base or as a concrete aggregate, a proper plant with at least two crushers, vibrating screens, magnets and conveyor belts have to be established. Once concrete rubble has been deposited at a recycling plant it is then broken by a pulveriser mounted on an excavator. Pieces of concrete waste broken to a suitable size are then crushed in a primary jaw crusher and then passed via conveyor belts into a cone crusher. The crushed material is passed through a set of vibrating screens and sieved on the way to a stock pile. After each crusher, the rotating magnets remove remains of steel reinforcement where as pickers manually remove other contaminants.
2.1.4 Properties Of Recycled Aggregate

Raw materials for production of the natural aggregates and RC aggregate contribute to some differences and variations of aggregate properties. Recycled concrete aggregate consists of natural aggregate coated with cement paste residue, pieces of natural aggregate, or just cement paste and some impurities. Relative amounts of these components, as well as grading, affect aggregate properties and classify the aggregate as suitable for production of concrete. There is a general consensus that the amount of cement paste has a significant influence on the quality, and the physical, mechanical and chemical properties of the aggregates and as such has potential influence on the properties of RC concrete.

2.1.4.1 Physical

The various physical properties of recycled aggregate are presented below.

2.1.4.1.1 Adhered paste and mortar

In recycled aggregates, the adhered mortar and paste are always present. The main factors which influence the quantity of adhered mortar in recycled aggregate crushed are water/cement ratio, original concrete strength and aggregate size. The grinding process has also influence on the amount of adhered mortar and the quality of recycled aggregates.

BCSJ (1978) indicated that approximately 20% of cement mortar was attached to 20 to 30mm size aggregate particles, while up to 0.3mm size filler fractions of recycled fine aggregate contain 45 to 65% of old cement mortar.
Hasaba (1981) stated that the quantity of adhered mortar in the original aggregate is proportional to the strength of the original concrete. The recycled aggregates which originated from the low strength concrete had less adhered mortar and the high strength concrete had more adhered mortar, when the crushed concrete was grinded with the same type of the machine and the same energy applied.

Hansen and Narud (1983) stated that the water/cement ratio of the original concrete influences the amount of adhered mortar to original aggregates and the quantity of adhered mortar increases with the decrease of the size of the aggregate, when the concrete is crushed with the same grinding machine and the same power.

2.1.4.1.2 Shape and surface texture

In particular, the shape of the coarse aggregate is an important characteristic that can affect the mechanical properties of concrete. The shape and surface texture of the coarse aggregate influence the strength of concrete by providing an adequate surface area for bonding with the paste or creating unfavorable high internal stresses. The surface texture of aggregate contributes significantly to the development of a physical bond between aggregate and cement paste.

Tasong et al. (1998) identified that the rough surface texture of the aggregate as contributing to a better bonding between aggregate and cement paste in concrete.

2.1.4.1.3 Bulk density

The bulk density or unit weight of an aggregate gives valuable information regarding the shape and grading of the aggregates. For a given specific gravity the angular aggregates shows a lower bulk density. Bulk density of aggregates is of
interest when dealt with light weight aggregates and heavy weight aggregates. In general, the saturated surface density of recycled aggregates is lower than that of natural aggregates, due to the low density of the mortar that is adhered to the original aggregate. It depends on the strength of original concrete and size of original aggregates.

Hansen et al. (1983) concluded that the recycled aggregate which obtained from a concrete of higher strength had higher density and also the saturated surface density depends on the kind of crushing machine employed and the energy used.

Hansen (1985) concluded that the density changes with the size of the aggregate and the amount of adhered mortar to the aggregate, when the concrete is grinded with the same type of the machine and the same energy applied. The density of recycled aggregate concrete reduces with smaller size of aggregates. The density decreases with the higher amount of adhered mortar to the aggregate.

Gonzalez et al. (2008) concluded that recycled aggregate concrete shows less dense than conventional concrete. Furthermore it is concluded that by addition of silica fume to the recycled aggregate concrete and conventional concrete, reduces the density.

Tam et al. (2008) concluded that as cement mortar density of around 1.0 to 1.6mg/cum is less than that of natural aggregate particles at around 2.6mg/cum, the lower the density of demolished concrete samples, the higher the cement mortar content will be. The demolished concrete density ranges between 2269kg/cum and 2432kg/cum.
2.1.4.1.4 Specific gravity

Hansen et al. (1983) investigated that the specific gravity decreases from 4.5 to 7.6% when compared with specific gravity of natural aggregate.

Topcu et al. (2004) investigated that the specific gravity of Waste Concrete Aggregates (WCA) was lower than normal crushed aggregates. The reason for this was thought to be the fact that there was a certain proportion of mortar over these aggregates.

Prasad et al. (2007) noted that the specific gravity of demolished concrete aggregates is lower than that of natural aggregate. The average specific gravity of aggregate usually varies from 2.6 to 2.8.

2.1.4.1.5. Water absorption

Hansen et al. (1983) found that the water absorption is 8.7% for the material that is 4–8mm in size, 3.7% for the material that is 16-32mm in size and the absorption capacity of recycled aggregate increased with a higher amount of adhered mortar.

Bairagi et al. (1993) concluded that very rapid rates of absorption are observed for recycle aggregate. Nearly 75% of the 24hour absorption capacity was attained in the first 30 minutes of the soaking period.

Ravindraraja (2000) demonstrated that the average value of water absorption in recycled aggregate was 6.35%, where as in natural aggregate it was 0.9%. The absorption capacity of recycled aggregates depends on the quality and quantity of adhered mortar. There was dependence between density and water absorption capacity. Recycle aggregates with adhered motor have lower density and higher water absorption capacity.
Gomez (2002) showed that the porosity increases considerably when natural aggregate is replaced by recycled coarse aggregate.

Topcu et al. (2004) investigated that the water absorption ratio was found to be much higher compared with that of normal crushed aggregates. This was attributable to mortar over these aggregates.

Gonzalez et al. (2008) concluded that recycled aggregate concrete shows more water absorption than conventional concrete. Furthermore it is concluded that by addition of silica fume to the recycled aggregate concrete and conventional concrete increases the water absorption.

Gao et al. (2008) found that the traditional testing approach for water absorption cannot give accurate results for recycled aggregate, based upon which, errors in concrete mix designs may result. Patches of cement pastes attached to the surface of recycled aggregate may affect water absorption in a manner different to conventional aggregate. Because of this, the standard duration of 24 hour of saturation is not suitable for recycled aggregate. In order to affect by the amount of cement paste sticking on the aggregate, it varies from the site to site after crushing from which the recycled aggregate was generated. In order to obtain the water absorption rates and corresponding soaking time, real-time assessment of water absorption is proposed to provide values of water absorption at different time intervals. Further, the proposed method can avoid the removal of cement paste during the soaking and drying process of recycled aggregate sample. This approach is simple and more accurate in measuring the genuine water absorption rate of recycled aggregate. This method has been tested and proven to be a good alternative for measuring water absorption of recycled aggregate.
Chakradhara rao et al. (2011) observed that the volume of voids and water absorption of recycled aggregate concrete are 2.61 and 1.82% higher than those of normal concrete due to the high absorption capacity of old mortar adhered to recycled aggregates.

2.1.4.2 Mechanical

The various mechanical properties of recycled aggregate are as follows.

2.1.4.2.1. Abrasion

With respect to recycled aggregates the value of Los-Angles abrasion changes depending on the strength of the original concrete, the amount of adhered mortar and the original aggregate quality.

Hansen et al. (1983) found that the Los-Angels abrasion loss value is 22.4% for aggregates sized 16-32mm and 41.4% for aggregates sized 4-8mm which were produced from high strength original concrete.

2.1.4.3. Durability properties

The various durability properties of recycled aggregate are as follows.

2.1.4.3.1. Sulphate soundness

The Sulphate soundness guarantees the aggregates resistance to freezing and thawing cycles. The percentage loss of weight of recycled aggregates exposed to sulphates solution depends to a great extent on the composition of the tested aggregates, as well as the type of original concrete and the method of crushing.
BCSJ (1978) verified that the loss of weight after five cycles changed from 18.4 to 58.9\% with respect to coarse recycled aggregates and by using the fine recycled aggregates values were from to 7.4 to 20.8\%.

Fergus (1981) found that the loss of sulphate weight to be between 0.9 to 2.0\% with respect to coarse recycled aggregates, and 6.8 to 8.88\% with regard to fine recycled aggregates.

Kasai (1985) concluded that the sulphate soundness test is unsuitable for evaluation of the durability of recycled aggregates.

2.1.4.3.2. Chemical-mineralogical characteristics

Limbachiya et al. (2007) concluded that commercially produced coarse RCA has chemical and mineralogical characteristics suitable for use in new concrete production. And also indicate that for coarse RCA samples obtained by crushing C & D debris from different sites, there was no significant variation in these characteristics, indicating no significant effect, if adequate quality control criteria during RCA production are being adopted. X-ray diffraction analysis results indicated the presence of calcite, port-landite and minor peaks of muscovite/illite in recycled aggregates, although they were directly proportioned to their original composition. Furthermore showed that up to 30\% coarse RCA (when used as direct replacement of natural gravel) has no influence on the main three oxides (SiO$_2$, Al$_2$O$_3$ and CaO) of concrete, but there after there is a marginal reduction in SiO$_2$, and increase in Al$_2$O$_3$ and CaO contents with increase in RCA content, reflecting the composition of the original material. Similar trends were observed in concrete produced using RCA samples obtained from three different C & D sources.
2.1.5 Recommendations

Some of the recommendations given by the RILEM and Oikonomou (2005) are discussed below.

According to RILEM, for the application of the recycled aggregates in the production of concretes, besides fulfilling all the specifications that have been defined in Table 2.1.

Table: 2.1 Specifications of RCA as per RILEM

<table>
<thead>
<tr>
<th>Mandatory requirements</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. dry particle Density Kg/cum)</td>
<td>1500</td>
<td>2000</td>
<td>2400</td>
<td>ISO 6783 &amp; 7033</td>
</tr>
<tr>
<td>Max. Water absorption (%)</td>
<td>20</td>
<td>10</td>
<td>3</td>
<td>ISO 6783 &amp; 7033</td>
</tr>
<tr>
<td>Max. content of foreign materials (metals, glass, soft material &amp; Bitumen) (%)</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>Visual</td>
</tr>
<tr>
<td>Max. content of metals (%)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Visual</td>
</tr>
<tr>
<td>Max. Content of organic material (%)</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>NEN 5933</td>
</tr>
<tr>
<td>Max. content of defiler (&lt;0.063mm) (%)</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>PrEN 933-1</td>
</tr>
<tr>
<td>Max. content of sand (&lt;4mm) (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>PrEN 933-1</td>
</tr>
<tr>
<td>Max. content of sulphate (%)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>BS 812- Part 118</td>
</tr>
</tbody>
</table>

Oikonomou (2005) proposed a guidance of tests and limits of RAC in order to be used as a basis for pilot and long scale works where the use of RCA can be estimated as more economic and friendlier to environment. Proposed basic tests and limits of RCA are shown in table 2.2.
Table 2.2 Basic tests and limits of RCA (Oikonomou (2005))

<table>
<thead>
<tr>
<th>Tests</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity, kg/cum, min</td>
<td>2.2</td>
</tr>
<tr>
<td>Water absorption, %, m/m, max</td>
<td>3</td>
</tr>
<tr>
<td>Foreign ingredients, %, m/m, max</td>
<td>1</td>
</tr>
<tr>
<td>Organic ingredients, %, m/m, max</td>
<td>0.5</td>
</tr>
<tr>
<td>Sulphate ingredients, %, m/m, max (as SO$_3$)</td>
<td>1</td>
</tr>
<tr>
<td>Amount of sand, %, m/m, max (&lt;4 mm)</td>
<td>5</td>
</tr>
<tr>
<td>Amount of filler, %, m/m, max (&lt;0.063 mm)</td>
<td>2</td>
</tr>
<tr>
<td>Resistance to abrasion/degradation by the use of L.A. machine, %, max</td>
<td>40</td>
</tr>
<tr>
<td>Soft granules, %, max</td>
<td>3</td>
</tr>
<tr>
<td>Soundness, loss, %, max</td>
<td>10</td>
</tr>
<tr>
<td>Sand equivalent, %, min</td>
<td>80</td>
</tr>
</tbody>
</table>

2.1.6 Mix design

Bairagi et al. (1990) identified the most suitable method of mix design for recycled coarse aggregate, amongst the available conventional methods of mix design. An influencing parameter was identified and an empirical relation was suggested to modify the influencing parameter. Mix design parameters thus obtained, enable recycled coarse aggregate concrete to attain the desired and designed target strength without attempting any trail mixes. The suggested modified procedure, however, demands 10% more cement which was considered quite reasonable and acceptable in view of the inferior quality of recycled aggregate. Of the four methods (IS code method, ACI method, RRL method and surface angularity index method) of mix
design ACI method had been found to be more appropriate for the design of recycle aggregate concrete.

2.1.7 Properties of Recycled Aggregate Concrete

Recycled aggregates used in concrete production have less density and more absorption capacity than conventional aggregates due to the adhered mortar. Consequently, in concrete made with recycled aggregates two interfacial transition zones are present: the existing interface between the original aggregate and the adhered mortar, and the new interface between the old and new mortar. The existing interface cannot be improved, and it is very important to achieve an effective new interface.

2.1.7.1 Properties of fresh concrete

The various properties of fresh concrete are discussed below.

2.1.7.1.1 Water demand and workability

In accordance with Hansen et al. (1983) and Ravindrarajah et al. (1985), recycled aggregate concrete made with recycled coarse aggregates and natural sand needs 5% more water than conventional concrete in order to obtain the same workability. If the sand was also recycled, 15% more amount of water was necessary to obtain the same workability.

Hansen (1986) concluded that the recycled aggregates in concrete production must be used in a condition of near saturation point to decrease the absorption capacity.
The recycled aggregate concrete be dosed, mixed, transported, placed, and compacted in the same way as conventional concrete.

Malhotra (1978) and Kumar Roy et al. (1988) concluded that the workability of recycled aggregate concrete can be maintained on par with the conventional concrete if the additional water demand of 5 to 8% required by a recycled aggregate concrete is approximately met with.

Bairagi et al. (1993) concluded that the workability of recycled aggregate concrete had been affected, but from a practical point of view all mixes have shown the same degree of workability. Loss of workability in the first 10 minutes was progressively greater with increase in replacement ratio.

Topcu et al. (1995) concluded that the workability of waste concrete aggregate is low and could be explained the higher water absorption of waste concrete aggregate.

Topcu et al. (1997) concluded that the slump values decreases where by waste concrete aggregate increases. The slump values are 75mm for waste concrete aggregate concrete and 100mm for normal aggregate concrete. The most important reason for this is that waste concrete aggregate has cement paste debris over that. The water in the mixture decreases because of the cement paste debris and also the workability of the mixture decreases.

Poon et al. (2004) concluded that the moisture states of the aggregates affected the change of slump of the fresh concrete. Oven dried aggregates led to a higher slump and quicker slump loss, while saturated surface dry and air dried aggregates had normal initial slumps and slump losses. The initial slump of concrete was strongly dependent on the initial free water content of the concrete mixes.
Topcu et al. (2004) investigated that the recycling waste concrete aggregates in concrete production raises the problem of workability. In particular, concrete with more than 50% waste concrete aggregates experiences more workability problem.

Tu et al. (2006) demonstrated that the recycled aggregates are not suitable for use in the production of High Performance Concrete (HPC) due to their relatively high absorption capacity, unstable properties and weaker strength. Such inadequacies can be overcome through carefully examining the characteristics of recycled aggregates and then adopting proper mixing procedure. Recycled aggregates from demolished construction wastes were examined and the Densified Mixture Design Algorithm (DMDA) was applied in the design of HPC. Results showed that HPC specimens containing recycled aggregates can be designed to have a slump more than 180 mm and a slump flow larger than 550 mm. However, HPC specimens with high amount of recycled aggregates and cement added loose their high-flowing and self-consolidating characteristics after 1 hour due to their greater water absorption.

2.1.7.1.2 W/C Ratio

Tavakoli et al. (1996) demonstrated that concrete made with 100% recycled aggregate with lower W/C ratio than the conventional concrete can have a larger compressive strength. When the W/C ratio is the same the compressive strength of concrete made with 100% recycled aggregate was lower.

2.1.7.1.3 Cement quantity

In accordance with Hansen (1985) and other researches in order to achieve the same compressive strength as in conventional concrete it is necessary to use more
cement (5-9%) in concrete made with 100% recycled aggregates. The values depend on the quality of aggregate. When recycled fine aggregates are also used 15-20% more cement could be necessary.

2.1.7.1.4 Density and air content

Hansen et al. (1983) concluded that fresh concrete made with 100% recycled aggregates have higher and more varied natural contents than conventional fresh concrete.

Hansen (1985) concluded that the natural air content of recycled aggregate concrete may be slightly higher than that of control concretes made with conventional concrete. But it is certainly possible to produce recycled aggregate concrete in the laboratory with no significant increase in air content compared with control mix.

Topcu et al. (1997) concluded that the unit weight of waste concrete aggregate is 2235 kg/cum and the unit weight of normal concrete is 2370 kg/cum. This decline is directly connected with the fact that the unit weight of the waste concrete aggregate concrete is lower than the normal aggregate concrete. The ultrasound velocity is 92-93 $\mu$s for waste concrete aggregate concrete and 69-70 $\mu$s for normal concrete, and it shows that the air voids become wider in the concrete and the strength of concrete decreases.

2.1.7.1.5 New interfacial transition zone

In conventional concrete the unique interfacial transition zone is presented between the mortar paste and the aggregates.
Concrete made with recycled aggregate have an additional Interfacial Transition Zone (ITZ) between the old adhered mortar to the original aggregate and the new mortar. These zones have to be considered when the concretes permeability and strength are studied.

Otsuki et al. (2003) concluded that the quality of recycled aggregate, in terms of adhesive mortar strength, affects the strength of recycled aggregate concrete when the water-binder ratio is low, however, the quality of recycled aggregate concrete does not affect the strength of recycled aggregate concrete when the water-binder ratio is high. In case of a high water-binder ratio concrete, where the old ITZ is stronger than the new ITZ, the strength of recycled aggregate concrete was equal to that of normal aggregate concrete. On the other hand, in case of a lower water-binder ratio, where the old ITZ is weaker than the new ITZ, the strength of the recycled aggregate concrete is lower than that of normal aggregate concrete.

Tokyay et al. (2004) observed that ITZ becomes critical for larger size of aggregates and lower w/c ratio mortar matrices. The negative effect of smooth surface texture of the aggregate and the larger difference between aggregate and matrix moduli of elasticity on the properties of ITZ was of paramount importance for the low w/c ratio composites. The effect of reduced bond properties of ITZ relative to its matrix was reflected in the lower critical stress levels for the low w/c ratio composites with larger aggregates.

Shui et al. (2004) observed that the high-performance concrete and normal-strength concrete recycled aggregates induced different interfacial transition zone microstructures in the recycled aggregate concrete. A relatively dense interfacial zone was present in high-performance recycled aggregate concrete where as a loose and
porous product layer filled the normal-strength concrete interfacial zone. The interfacial transition zone microstructure in concrete with recycled aggregates appeared to be an important factor in governing strength development of the recycled aggregate concrete. It is expected that the mechanical properties of recycled aggregate concrete can be improved by modifying the surface properties and the pore structure of the recycled aggregates.

Nagataki et al. (2004) evaluated that the complex nature of recycled concrete aggregates are susceptible to damage due to recycling. The laboratory produced recycled concrete aggregates were investigated using fluorescent microscopy and image analysis. Contrary to common opinion, micro-structural studies showed that adhered mortar is not always the primary parameter determining the quality of the recycled coarse aggregate. Sandstone coarse aggregate originally had defects in the form of voids and cracks. Further processing of the recycled coarse aggregate changed the micro-structural profile of the material and enhanced their properties.

Akcaoglu et al. (2004) demonstrated that with larger aggregates, low w/c ratio matrices result in more critical ITZs with a more condensed micro crack in a narrower region. This indicates that the adverse effect of the rigid aggregate becomes more pronounced with increased matrix quality and aggregate size. The role of ITZ and matrix on the damage process depends on the w/c ratio of the mixture. In high w/c mixtures, ITZ effect is more pronounced up to the onset of crack propagation, whereas it is important at rapid crack propagation in low w/c mixtures.

Katz (2004) summarised that scanning electron microscopy of recycled aggregates derived from the crushing of old concrete showed extensive cracking of the old cement paste that remained adhered to the natural aggregate. In addition,
contamination of the surface of the crushed concrete by small particles that were loosely connected to the aggregate were observed. Two treatments were evaluated, with the purpose of improving the surface properties of the recycled aggregates: one is impregnation of the recycled aggregate with a 10% by weight silica fume solution; and the other is ultrasonic cleaning of the recycled aggregate to improve loose particles from the surface. The silica fume treatment resulted in an increase of 23 to 33% and 15% in the compressive strength at ages 7 and 28 days, respectively. Ultrasonic treatment yielded a moderate increase of 7%, with no clear difference between early and late ages. It appears that silica fume impregnation improves both the interfacial transition zone between the recycled aggregates and the new cement matrix, and the mechanical properties of the recycled aggregate. As a result, early strength of new concrete increases significantly when the disparity between the properties of recycled aggregate and new cement matrix is relatively small and the filler effect of the silica fume is dominant. At a later age, after the cement matrix has strengthened, these effects are weaker, leading to a lesser influence on the strength. Cracking of the old cement matrix seems to have a strong influence on the properties of the recycled aggregate.

Tam et al. (2005) concluded that the two-stage mixing approach gives way for the cement slurry to gel up the recycled aggregate, providing a stronger ITZ by filling up the cracks and pores with recycled aggregate.

### 2.1.8 Mechanical Properties of Recycled Aggregate Concrete

The various mechanical properties of recycled aggregate concrete are as follows.
2.1.8.1 Compression

The behavior of various combinations of recycled aggregate and natural aggregate in compression is as follows.

2.1.8.1.1. Behaviour of recycled aggregate concrete produced with natural coarse aggregate and recycled fine aggregate

Concrete produced with recycled sand may behave differently from conventional concrete. When the entire natural sand is replaced by recycled sand part of the compressive strength is lost with respect to conventional concrete. Recycled sand reduces the freezing and thawing resistance. According to the researchers it is recommended to avoid the utilization of recycled aggregates smaller than 4 to 5mm.

2.1.8.1.2. Behaviour of recycled aggregate concrete produced with recycled coarse aggregate and recycled fine aggregate

Hansen et al. (1983) and Soshiroda (1983) obtained the compressive strength trend loss by increasing the recycled sand quantity in concrete. The recycled concrete loses half of its compressive strength when the entire natural sand is replaced with recycled sand. Moreover when the recycled sand is smaller than 2mm more loss of strength was produced. Furthermore, this recycled sand also had a tendency to diminish frost resistance. It was not recommended to use any recycled aggregate smaller than 2mm.
2.1.8.1.3. Behaviour of recycled aggregate concrete produced with recycled coarse aggregate and natural sand

Nixon (1978) concluded that the compressive strength of concrete made with 100% of recycled aggregate was 20% lesser than the conventional concrete.

Hansen et al. (1983) concluded that, not only the w/c ratio influences on compressive strength of concrete made with 100% of recycled aggregate, but the compressive strength of the recycled aggregate concrete also depends on the strength of the original concrete. The compressive strength of recycled aggregate concrete is strongly controlled by the combination of w/c ratio of the original concrete, when other factors are essential equal. Therefore dependence exists with respect to the new-old w/c ratio. When the w/c ratio of the original concrete is equal or lower than that of the recycled aggregate concrete, the resistance of the recycled concrete can be equal to or greater than the original one. However, when the w/c ratio of the original concrete is high, the original concrete strength will determine the new concrete strength. The coefficient variation of the compressive strength of a recycled aggregate does not differ too much from the established conventional concrete behaviours. However, it must be noted that in practice these results are not easily demonstrated. Since the w/c ratio is difficult to determine.

Hansen (1986) concluded that any variation in concrete production or in the properties used produces a variation of strength in the resultant concrete. The employment of different qualities of recycled aggregate in concrete production brings about an increase of the coefficient variation.
Bairagi et al. (1993) concluded that the average relative compressive strength varies from 98 to 94% when the replacement ratio is varied from 0.25 to 0.50. For the replacement ratio 1.0 the average relative compressive strength was 86%.

Oliveira et al. (1996) studied the effects of three different moisture conditions from the recycled aggregate are compared (dry, saturated and semi-saturated) and concluded a slight decrease in the compressive strength of the concrete made from dry and saturated recycled aggregates.

Salem et al. (1998) concluded that the compressive strength of concrete made with 100% of recycled aggregate increases by 2% from 7 to 28 days with respect to the 16% increasing conventional concrete. This could be due to either the absorption capacity of the recycled aggregate or the bad adherence of the aggregate with the cement paste.

Giaccio et al. (1998) demonstrated that the type of coarse aggregate increases as strength level increases, as matrix strength is close to rock strength the probability of crack development through aggregates increases, and the mechanisms of cracking are modified compared with conventional concrete. At the same time, there is a strong relationship between interface strength and concrete failure behavior. The strength of the composite differs from the strength of the component phases due to limitations in bond strength. Adhesion and mechanical interlocking between matrix and aggregates are the main factors responsible for adherence development.

Limbachiya et al. (2000) showed that 30% coarse recycled concrete aggregate concrete had no effect on the ceiling strength of concrete, but thereafter this reduces with increase in recycled concrete aggregate content. A method had been established
to take account of the effects of recycled concrete aggregate on compressive strength, requiring a simple adjustment to the water/cement ratio.

Otsuki et al. (2003) concluded that the improvements in strength of recycled aggregate concrete can be achieved by using the double mixing method in the case of higher water binder ratio concrete.

Katz (2003) concluded that the properties of the recycled aggregates crushed at different ages were quite similar. Concrete made with 100% recycled aggregates was weaker than concrete made with natural aggregates at the same w/c ratio. When the new concrete was made from the same type of OPC and the same w/c ratio as the old concrete, the strength reduction was up to 25%, regardless of the crushing age of the old concrete. With white cement, the reduction was 30 to 40%, depending on the crushing age of the old concrete (the white cement provides with 20% higher compressive strength than the OPC concrete at the same w/c ratio prepared with natural aggregate). The properties of recycled White Pozzalona Cement (WPC) concrete made with recycled aggregate at age 3 days significantly better than those of concretes made with aggregate crushed at age 1 or 28 days. Opposing trends were seen recycled OPC concrete in which the new cement matrix was weaker than that of the WPC concrete at the same w/c ratio. Two opposite mechanisms seem to affect the properties of the new concrete one is the physical properties of the old concrete and the other is the presence of un-hydrated cement in the recycled aggregate. These effects are prominent when the new cement matrix is significantly stronger than that the one in the old concrete. In such concrete, the combination of strength and cementing capacity of the recycled aggregates crushed at 3 days provides better strength over crushing ages of 1 or 28 days. In a weaker new cement matrix, this
effect is reversed and the new concrete made from recycled aggregates crushed at 3
days was slightly weaker than concrete made from aggregates crushed at 1 or 28 days.

Poon et al. (2004) concluded that for the concrete mixtures prepared with the
incorporation of recycled aggregates, the air dried (AD) aggregate concrete exhibited
the highest compressive strength. The saturated surface dry (SSD) recycled
aggregates seemed to impose the largest negative effect on the concrete strength, with
might be attributed to “bleeding” of excess water in the pre-wetted aggregates in the
fresh concrete. The aggregates in the AD (as received) state and contain not-more
than 50% recycled aggregates should be optimum for normal strength recycled
aggregate concrete production.

Topcu et al. (2004) investigated that the compressive strength decreased in both
control concrete and concrete with WCAs in parallel to w/c ratio. However,
compressive strength decreased in proportion to low w/c ratio in concrete with
WCAs.

Lin et al. (2004) investigated the procedure for assessing the optimal mixture
proportioning of concrete made with recycled concrete aggregates based on the
orthogonal array, ANOVA, and significance test with F statistic. The proposed
procedure provides a better way for understanding the real engineering behavior of
recycled concrete.

Shui et al. (2004) concluded that the concrete prepared with the recycled
aggregate derived from high-performance concrete developed higher compressive
strength than the concrete prepared with recycled normal-strength concrete aggregates
at all ages. In particular, the strength of the concrete with HPC recycled aggregates
reached the level of the concrete prepared with the crushed natural granite aggregates
after 90 days of curing. The difference in the strength development between the concretes with high-performance concrete and normal-strength concrete recycled aggregates was due to the differences in both the strength of the coarse aggregates and the microstructural properties of the interfacial transition zones.

Tam et al. (2005) concluded that the two-stage mixing approach can provide an effective method for enhancing the compressive strength and other mechanical performance of RAC and thus, the approach opens up a wider scope of RAC applications.

Kheder et al. (2005) concluded that the compressive strength of RAC depends largely on the w/c ratio of the mix. It was possible to reach a compressive strength of 53.5 MPa by the use of binding mortar with strength of 52.4 MPa. The corresponding NAC strength was 55.2 MPa.

Xiao et al. (2005) concluded that the compressive strengths including the prism and the cube compressive strengths of RAC generally decreases with increasing RAC contents. But the ratio of the prism compressive strength and cube compressive strength is higher than that of normal concrete. The failure mode of RAC is a shear mode under the experimental conditions. The failure process of RAC is relatively short. The inclination angle between the failure plane and the the vertical load plumb is about 63 to 79 degrees.

Etxeberria et al. (2007) concluded that the concrete made with 100% of recycled coarse aggregate has 20 to 25% less compressive strength than conventional concrete at 28 days, with the same effective w/c ratio and cement quantity. Concrete made with 100% of coarse recycled aggregates requires high amount of cement to achieve a high compressive strength and consequently is not an economic proposition as it is not cost
effective. These recycled aggregates should be used in concrete with low-medium compressive strength (20-45MPa). Moreover, the adhered mortar in recycled aggregates is lower in strength than conventional aggregates and the new paste. Consequently, the weakest point in concrete made with coarse recycled aggregates employing a cement paste of medium-high strength (45-60MPa) can be determined by the strength of the recycled aggregates or their adhered mortar. Medium compressive strength (30 to 45MPa) concrete made with 25% of recycled coarse aggregate achieves the same mechanical properties as that of conventional concrete employing the same quantity of cement and the equal effective w/c ratio. Medium compressive strength concrete made with 50% or 100% of recycled coarse aggregates needs 4 to 10% lower effective w/c ratio and 5 to 10% more cement than conventional concrete to achieve the same compressive strength at 28 days.

Rahal (2007) concluded that the 28 days target compressive strength for all five mixes of RCA (20, 25, 30, 40 and 50MPa) were achieved except for the 40 and 50 MPa where the observed strength was slightly lower than the target strength. On the average, the 56 day cube strength was 5% and 3% higher than the 28 day strength for RAC and NAC, respectively. RAC and NAC showed similar trends in compressive strength development, with relatively faster strength gain in NAC up to an age of 7 days. The 28 day cube strength in RAC showed a scatter somewhat similar to that in NAC. The average coefficient of variation is 2.73% for RAC and 2.60% for NAC. This relatively small variation could be due to the limited number of sources of recycled aggregates.

Eguchi et al. (2007) concluded that as the replacement ratio of recycled coarse aggregate increases the compressive strength decreases. However by estimating the
decrease in quality by relative quality values and adjusting the replacement ratio, the quality required for the concrete can be ensured.

Shi Congkou et al. (2007) concluded that the compressive strength decreased as the recycled aggregate content increased. However the reduction could be adequately compensated by the use of a lower W/B ratio. At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as a partial replacement of cement decreased the compressive strength.

Gonzalez et al. (2007) concluded that it was possible to produce a recycled aggregate concrete (with 50% of recycled concrete aggregates) with almost the same compressive strength by changing quantity of cement 6.2% higher than the one of conventional concrete.

Ann et al. (2008) concluded that the compressive strength of concrete containing recycled aggregate at 7, 28, 90 and 180 days was lower than that of the control concrete specimens, but was recovered by replacing for cement in binder with 30% pulverized fuel ash (PFA) and 65% ground granulated blast furnace slag (GGBS), which were, however, less effective in increasing the tensile strength at 28 days.

Tam et al. (2008) demonstrated that there are correlations among the characteristics of the Recycled Demolished Concrete (DC) samples, and their Recycled Aggregate (RA) and Recycled Aggregate Concrete (RAC). It is shown that the inferior quality of DC can lower the quality of their RA and RAC. It is important to measure the characteristics of DC to provide a pre-requisite consideration for their RA and RAC applications. This can save time and cost for the production of inferior quality RA and ensure that high quality RA is produced for higher grade concrete.
applications. RAC design requirements can also be developed at the initial concrete demolition stage.

Gonzalez et al. (2008) concluded that it was possible to produce RC (with 50% of RC aggregates and a quantity of cements 6.2% higher than the one in CC) with almost same strength as CC and with the same consistency. The compressive strength of recycled concrete with silica fume was also similar to that of conventional concrete with this admixture. However, in all cases after 28 days (following the pozzolanic reaction) the RCS displayed greater compressive strength than the CC. In other words, the addition of 8% silica fume to mixes containing recycled aggregates was found to be beneficial in terms of compressive strength. Recycled concrete (RC) and control concrete (CC), recycled concrete with silica fume (RCS) and control concrete with silica fume (CCS) showed similar trends in compressive strength development.

Chakhradhara rao et al. (2011) observed that the concrete cured in air after 7 days of wet curing shows better strength than concrete cured completely under water for 28 days for all coarse aggregate replacement ratios.

2.1.8.2 Behavior of recycled aggregate concrete in tension

BCSJ (1978) and Ravindrarajah et al. (1985) demonstrated that there are no great differences in the tensile strength of recycled course and natural sand concrete with respect to conventional concrete. However if recycled sand replaces the natural sand used in the concrete employing recycled coarse aggregates then the tensile strength diminishes 20% with respect to conventional concrete.
Bairagi et al. (1993) concluded that the relative split tensile strength varies from 94 to 90% when the replacement ratio is varied from 0.25 to 0.50. For the replacement ratio 1.0 the average split tensile strength was 60% less.

Otsuki et al. (2003) concluded that the improvements in strength of recycled aggregate concrete can be achieved by using the double mixing method in the case of higher water binder ratio concrete.

Akcaoglu et al. (2004) demonstrated that the interfacial bond was observed to be the determining factor for the tensile strength and played little role on the compressive strength. The tensile strength decreases as the aggregate size increases. The rate of tensile strength reduction with increasing single aggregate size becomes higher in High Strength Concrete.

Kheder et al. (2005) concluded that the splitting tensile strength of NAC was higher than that of mortar, while RAC was lower than that of mortar for mixes of high strength.

Shi Cong kou et al. (2007) concluded that the splitting tensile strength decreased as the recycled aggregate content increased. However the reduction could be adequately compensated by the use of a lower W/B ratio. At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as a partial replacement of cement decreased the splitting tensile strength.

Gonzalez et al. (2007) concluded that it was possible to produce a recycled aggregate concrete (with 50% of recycled concrete aggregates) with almost the same split tensile strength by changing quantity of cement 6.2% higher than the one of conventional concrete.
2.1.8.3. Behavior of recycled aggregate concrete in flexure

Ravindrarajah et al. (1985) demonstrated that there was no great difference between the flexural strength of concrete made with recycled coarse aggregate and natural sand with conventional concrete.

Bairagi et al. (1993) concluded that the relative modulus of rupture varies from 94 to 87% when the replacement ratio is varied from 0.25 to 0.50. For the replacement ratio 1.0 the average split tensile strength was 74%.

Oliveira et al. (1996) studied the effects of three different moisture conditions from the recycled aggregate are compared (dry, saturated and semi-saturated) and concluded that the decrease is especially noticeable in flexural strength in the concrete with the saturated recycled aggregates.

Kheder et al. (2005) concluded that the flexural strength of both NAC and RAC were lower than that of mortar by about 5 to 28% and 20 to 39%, respectively. The difference decreased with the increase in compressive strength of the mix.

Casuccio et al. (2008) resulted that the increase in bond strength and reduction in stiffness that take place when natural coarse aggregate is replaced by recycled aggregate, increases the elastic compatibility between concrete phases (mortar and coarse aggregates) modifying the fracture process. This has a special interest in normal strength concrete. Compared with concrete including natural crushed stone as coarse aggregate, RAC has a lower stiffness, shows smaller reduction in tensile or compressive strengths and also show clear decrease in the energy of fracture and in the size of the fracture zone. A reduction in branching and meandering of cracks on the fracture surfaces was also observed.
2.1.8.4 Stress strain behavior of recycled aggregate concrete

Bairagi et al. (1993) concluded that variation in replacement ratio affects the stress strain relationship of a concrete mix. Its curvature was greater as the replacement ratio increases, thus giving reduced values of modulus of elasticity.

Topcu et al. (1995) proposed that with the increase of waste concrete aggregate amount in mixture the values of toughness, plastic energy capacity and elastic energy capacity decreases.

Akcaoglu et al. (2004) demonstrated that in High Strength Concrete (HSC) the stress levels corresponding to the onset of crack propagation decreases with increasing aggregate size while it was nearly constant in Low Strength Concrete (LSC) containing the same size aggregates. The critical stress at which rapid and continuous crack propagation starts is around the ultimate and showed no significant size in LSC whereas it is lower in HSC and decrease with increasing aggregate size.

Xiao et al. (2005) concluded that the RCA replacement percentage has a considerable influence on the stress-strain curves of RAC. For all cases 0 to 100%, the stress-strain curves show a similar behavior. The stress-strain curves of RAC indicate an increase in the peak strain and a significant decrease in the ductility as characterised by their descending portion. The peak strain of RAC is higher than that of normal concrete. It increases with the increase of RCA contents. For a RCA replacement percentage equals to 100%, the peak strain was increased by 20%.

Bhikshma et al. (2010) concluded that the Saenz (1964) mathematical model is successfully evaluated and validated for all recycled aggregate concrete mixes. Stress strain values for various grades and percentages of recycled coarse aggregates of
developed exclusively for recycled aggregates concrete mixtures, and they are validated for all concrete mixtures.

**2.1.8.5 Young’s modulus**

The old mortar which is adhered to the recycled aggregates has a low modulus of elasticity, consequently concrete made with recycled aggregates will always have a lower modulus of elasticity than that of conventional concrete.

Hansen et al. (1985) reported that both dynamic and static modulus of elasticity reduce between 14 and 28% for recycled aggregate concrete. The modulus of elasticity of a recycled aggregate concrete that consisted of a low quality crushed mortar to be 45% lower than the modulus of elasticity of a corresponding control concrete made with conventional aggregates.

Bairagi et al. (1993) concluded that the relative modulus of elasticity varies from 93 to 85% when the replacement ratio is varied from 0.25 to 0.50. For the replacement ratio 1.0 the average split tensile strength was 71%.

Topcu et al. (1995) reported that the modulus of elasticity of recycled aggregate concrete is 80% less than normal concrete.

Xiao et al. (2005) concluded that the elastic modulus of RCA is lower than that of the normal concrete. It decreases as the RCA content increases. For a RCA replacement percentage equal to 100%, the elastic modulus is reduced by 45%.

Kheder et al. (2005) concluded that modulus of elasticity of NAC and RAC exceeded that of corresponding mortar by about 40 and 10%, respectively. The modulus of elasticity of RAC is about 20 to 25% lower than NAC.
Rahal (2007) concluded that for concrete with cylindrical strengths between 25 and 30 MPa, the modulus of elasticity of RAC was only 3% lower than that of NAC. The ACI equation overestimated the secant stiffness. The strains at peak compressive stress in RAC were 5.5% larger than that in NAC. This difference is not likely to have any significant implications on structural designs.

Eguchi et al. (2007) concluded that as the replacement ratio of recycled coarse aggregate increases the elastic modulus decreases. However by estimating the decrease in quality by relative quality values and adjusting the replacement ratio, the quality required for the concrete can be ensured.

Shi Cong kou et al. (2007) concluded that the static modulus of elasticity decreased as the recycled aggregate content increased. However the reduction could be adequately compensated by the use of a lower W/B ratio. At the same recycled aggregate replacement level and W/B ratio, the use of fly ash as a partial replacement of cement decreased the static modulus of elasticity.

Poon et al. (2007) concluded that the use of recycled aggregate decreased the elastic modulus; the addition of fly ash could be used to offset this detrimental effect. ACI equation slightly overestimates the elastic modulus of recycled aggregate concrete.

Gonzalez et al. (2008) concluded that a reduction in the static elastic modulus of elasticity was observed in all the recycled aggregate concrete. The addition of silica fume did not improve the static elastic modulus of elasticity.
2.1.9  Relationships Between the Mechanical Properties

Ravindrarajah et al. (1985) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[
\text{Static Modulus of Elasticity} \quad (E) = 4.63 f_{cy}^{0.50} \quad --- \ (2.1) \\
(E) = 7.77 f_{cu}^{0.33} \quad --- \ (2.2)
\]

\[
\text{Dynamic Modulus of Elasticity} \quad (E_D) = 6.19 f_{cy}^{0.50} \quad --- \ (2.3) \\
(E_D) = 13.05 + 3.48 f_{cu}^{0.50} \quad --- \ (2.4)
\]

Being \( f_{cy} \) and \( f_{cu} \) are Cylindrical and Cube compressive strength respectively in MPa.

Ravindrarajah (1987) defined the modulus of elasticity as :

\[
E = 5.31 f_{cu}^{0.50} + 5.83 \ (\text{for Conventional concrete}) \quad --- \ (2.5) \\
E = 3.02 f_{cu}^{0.50} + 10.67 \ (\text{for recycled aggregate concrete}) \quad --- \ (2.6)
\]

Kakizaki et al. (1988) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[
E_c = 1.9 \times 10^5 \times (\gamma /2300)^{1.5} \times (f_{cu}/2000)^{0.5} \quad --- \ (2.7)
\]

Dillmann et al. (1998) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[
E_c = 634.43 f_{cu} + 3057.60 \quad --- \ (2.8)
\]

Dhir et al. (1999) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[
E_c = 370 f_{cu} + 13100 \quad --- \ (2.9)
\]

Mellmann (1999) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[
E_c = 378 f_{cu} + 8242 \quad --- \ (2.10)
\]
Zilch et al. (2001) presented models for modulus of elasticity for recycled aggregate concretes as follows:

\[ E_c = 9100 \times (f_{cu} + 8)^{0.33} \times (\gamma / 2400)^2 \]  --- (2.11)

Kheder et al. (2005) established the following relationship between NAC, RAC and binding mortar.

The relationship between NAC, RAC and mortar modulus of elasticity and their cylinder compressive strengths are:

\[ E_{cn} = 5.323 f'_{cn}^{0.453} \]  --- (2.12)
\[ E_{cr} = 4.993 f'_{cr}^{0.422} \]  --- (2.13)
\[ E_m = 6.631 f'_{cm}^{0.315} \]  --- (2.14)

The relationship between the cylinder/cube strength ratio and cylinder compressive strength of NAC, RAC and mortar, respectively are:

\[ R = 0.762 + 0.0027 f'_{cn} \]  --- (2.15)
\[ R = 0.657 + 0.0033 f'_{cr} \]  --- (2.16)
\[ R = 0.691 + 0.0009 f'_{cm} \]  --- (2.17)
\[ R = 0.474 + 0.0137 E_c \]  --- (2.18)

The relationship between the flexural strength of NAC and RAC to that of the corresponding binder mortar is:

\[ f'_{cn} = 3.535 f'_{cm}^{0.6895} \]  --- (2.19)
\[ f'_{cr} = 1.813 f'_{cm}^{0.8384} \]  --- (2.20)

The relationship between the cylinder compressive strength of NAC and RAC to the corresponding cylinder compressive strength of the binder mortar is:

\[ f_m = 1.379 f_{rm}^{0.689} \]  --- (2.21)
\[ f_{rr} = 1.163 f_{rm}^{0.697} \]  --- (2.22)
The relationship between the flexural strength and compressive strengths for NAC, RAC and the binder mortar is:

\[
\begin{align*}
  f_{m} &= 0.610 f_{cn}^{0.558} \quad \text{--- (2.23)} \\
  f_{rr} &= 0.762 f_{cr}^{0.473} \quad \text{--- (2.24)} \\
  f_{tm} &= 0.846 f_{cn}^{0.560} \quad \text{--- (2.25)}
\end{align*}
\]

The relationship between the splitting tensile strength of binding mortar upon those of NAC and RAC are:

\[
\begin{align*}
  f_{tn} &= 1.979 f_{tm}^{0.616} \quad \text{--- (2.26)} \\
  f_{tr} &= 1.741 f_{tm}^{0.528} \quad \text{--- (2.27)}
\end{align*}
\]

The relationship between the split tensile strength and compressive strengths for NAC, RAC and the binder mortar are:

\[
\begin{align*}
  f_{tn} &= 0.328 f_{cn}^{0.692} \quad \text{--- (2.28)} \\
  f_{tr} &= 0.568 f_{cr}^{0.499} \quad \text{--- (2.29)} \\
  f_{tm} &= 0.218 f_{cn}^{0.782} \quad \text{--- (2.30)}
\end{align*}
\]

Where, \( E_{cm}, E_{cn}, E_{cr} \) : Modulus elasticity of mortar, NAC, RAC respectively

\( f_{cm}, f_{cn}, f_{cr} \) : Cylinder compressive strength of mortar, NAC, RAC respectively

\( f_{im}, f_{in}, f_{ir} \) : Modulus of rupture of mortar, NAC, RAC respectively

\( f_{im}, f_{in}, f_{ir} \) : Split tensile strength of mortar, NAC, RAC respectively

\( R \) : Ratio of cylinder to cube compressive strength

Zhang et al. (2006) established the relationship between compressive strength and mass density as follows:

\[
  f_{cu} = 0.069 \gamma - 116.10 \quad \text{--- (2.31)}
\]
Where, ‘$f_{cu}$’ is cube compressive strength in MPa and ‘$\gamma$’ is the mass density in kg/cum

The relationship between split tensile strength and cube compressive strength as follows:

$$f_{sp} = 0.24 f_{cu}^{0.65}$$  \text{--- (2.32)}

Where, ‘$f_{sp}$’ is split tensile strength and ‘$f_{cu}$’ is cube compressive strength in MPa.

The relationship between flexural strength and compressive strength as follows:

$$f_{f} = 0.75 f_{cu}^{0.5}$$  \text{--- (2.33)}

Where, ‘$f_{f}$’ is flexural strength and ‘$f_{cu}$’ is cube compressive strength in MPa.

The relationship between modulus of elasticity and compressive strength as follows:

$$E_c = 7770 f_{cu}^{0.33}$$  \text{--- (2.34)}

2.1.10 Sound Absorption Characteristics

Park et al. (2005) concluded that the difference between the target void ratio and the actual measured void ratio of porous concrete for noise reduction using recycled waste concrete aggregate of 5 to 13mm in size was less than 1.7% and the content of the recycled aggregate had little influence on the void ratio. The sound absorption characteristics of the porous concrete by the impedance tube demonstrated the frequency range where the absorption coefficient is optimum moved to the high frequency range as the targeted void ratio increased and the noise reduction coefficient was the highest at the value of 25%. However, the sound absorption area ratio increased as the target void ratio increased, becoming the highest when the target void ratio was 30%. It was established that the sound absorption ability of the porous
concrete prototype for the field application designed to have the targeted void ratio of 25% and content of the recycled aggregate of 50% by the reverberation room method increased from 0.12 to 0.86 as the center frequency increased from 100 to 5000 Hz and that the noise reduction coefficient was 0.6.

2.1.11 Durability Properties

According to Allexander et al. (1999) ranges of index values for concrete durability are tabulated in Table 2.3.

<table>
<thead>
<tr>
<th>Durability Class</th>
<th>Oxygen Permeability Index (OPI) (log scale)</th>
<th>Sorptivity (mm/sqrt (h))</th>
<th>Chloride conductivity (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&gt;10.0</td>
<td>&lt;6.0</td>
<td>&lt;0.75</td>
</tr>
<tr>
<td>Good</td>
<td>9.5 – 10.0</td>
<td>6.0-10.0</td>
<td>0.75 -1.50</td>
</tr>
<tr>
<td>Poor</td>
<td>9.0 – 9.5</td>
<td>10.0 – 15.0</td>
<td>1.50 – 2.50</td>
</tr>
<tr>
<td>Very poor</td>
<td>&lt;9.5</td>
<td>&gt;15.0</td>
<td>&gt;2.50</td>
</tr>
</tbody>
</table>

2.1.11.1 Permeability and water absorption

Limbachiya et al. (2000) concluded that up to 30% coarse RCA had no influence on the initial surface absorption (ISAT) measured at 10 minutes (ISAT-10) and thereafter ISAT-10 increased with RCA content. This is due to the increase proportion of cement paste in RCA, as the quantity of attached cement paste in the concrete with 100% coarse RCA increased by three times than that of concrete with 30% coarse RCA. And also concluded that up to 30% coarse RCA had no detrimental effect on air permeability, regardless of concrete strength. However, intrinsic air permeability found to increase with RCA content beyond this level.
Buyle-Bodin et al. (2002) examined that when both fine and coarse RA are used in the concrete, the permeability increases 6.5 times compared to coarse RA concrete and 13 times compares to that of NAC.

Olorunsogo et al. (2002) showed that for a given percentage of RA content, OPI of the concrete samples increases, the longer the duration of curing. Between the curing periods of 3 and 56 days and for the concrete mix containing 0% RA, OPI increased by 33.6%. Similar increases of OPI for the concrete mixes incorporating 50% and 100% RA were 37.6% and 38.2% respectively. Comparing the recommended values of OPI for concrete durability classified by Alexander et al. (1999), the 100% NA concrete attained the class status of ‘good’ at the curing age of 28 days with an OPI of 9.6, whilst the 50% RA concrete attained similar class status at 56 days with an OPI of 9.69. However 100% RA concrete only achieved a class status of ‘poor’ with the OPI value 9.22 at the curing age of 56 days. It is, however, possible that this value increase the longer the curing duration. This trend of reduction in OPI with increase in replacement levels of RA in a concrete mix was due to cracks and fissures in the attachment mortar over RA in turn create paths for ease of passage of fluids through the resulting concrete mix in which they are incorporated.

Zaharieva et al. (2003) showed that the recycled aggregate (both coarse and fine aggregates) concrete is significantly more permeable than natural aggregate concrete. A possible use of admixtures such as fly ash or silica fume could decrease significantly porosity and permeability of recycled aggregate (both coarse and fine aggregates) concrete.

Shui et al. (2004) investigated that the porous interfacial transition zone microstructure in the normal-strength concrete can be attributed to the higher porosity
and absorption capacity of recycled aggregate. The interfacial transition zone formation was related to moisture movement and chemical reactions in the recycled aggregate concrete.

2.1.11.2 Freezing and thawing resistance

Oliveira et al. (1996) studied the effects of three different moisture conditions from the recycled aggregate are compared (dry, saturated and semi-saturated) and concluded that the bad resistance to freeze-thaw of concretes with saturated and dry recycled aggregates and the good results of those made with semi-saturated aggregates.

Salem et al. (1998) concluded that the air entrained method is the best way to improve the frost resistance of recycled aggregate concrete; however this method decreases some of the concrete physical properties.

Limbachiya et al. (2000) concluded that the concrete produced using up to 100% coarse RCA had durability factor in excess of 95%, showing good freeze/thaw durability potential.

Zaharieva et al. (2004) concluded that the frost resistance of saturated recycled aggregate concrete (RAC) is not satisfying, and their use in structures exposed to severe climate is not recommended. The main reason seems to be the high total w/c ratio, including higher porosity and lower mechanical characteristics of RAC, as well as the frost resistance of RA themselves. First, they might contain unsound particles, which would be deteriorated by the repeated action of freezing-thawing cycles, and, second, RA could contribute to the frost damage by expelling water in to the surrounding cement paste during the freezing periods.
Gokce et al. (2004) demonstrated that non-air-entrained concrete is a serious handicap to achieve a good freezing and thawing resistance when it is used as recycled coarse aggregate in air-entrained concrete. Improper air void system of each independent aggregate particle converts the total voids system to a partial non-air-entrained system causing a poor freezing and thawing resistance. However, if an air-entrained concrete incorporates also air-entrained recycled course aggregate, this concrete has an entirely air-entrained voids system an excellent performance under freezing and thawing exposure. Although the beneficial effect of the further processing to reduce adhered mortar content was observed in the concrete made with non-air-entrained recycled coarse aggregate, this limited contribution was not enough to attain desired freezing and thawing resistance. On the other hand, reducing the adhered mortar content of a sound recycled concrete aggregate did not create a clear contribution to freezing and thawing resistance of the concrete. The presence of a small amount of non-air-entrained recycled coarse aggregate in the aggregate population would be enough to drastically reduce freezing and thawing resistance of the concrete. To ensure high freezing and thawing durability, only pure air-entrained recycled coarse aggregate with enough quality should be used in the mixture. Even though the matrix performance of the concrete incorporating non-air-entrained recycled coarse aggregate was considerably improved with a low w/b ratio of 0.30, the freezing and thawing resistance for a long term exposure could not be achieved. Only the concrete containing metakaolin performed relatively well and satisfied the durability limits resisting over 300cycles. Microscopic level investigation of the damage mechanism for the concretes incorporating non-air-entrained recycled coarse aggregate showed that deteriorated adhered mortar with heavy cracks first caused
disintegration of the recycled coarse aggregate itself, than the damaged particles behaved as local defects to distress the new mortar. After development of the crack network the concrete failed with heavy damage. If adhered mortar was frost resistance (air-entrained), recycled aggregate concrete did not show a serious sign of cracking. The severity of cracking was even lower than that of natural aggregate concrete. This was due to the pre-exposure defect potential of the sand stone coarse aggregate. The recycling process reduced the size of the original coarse aggregate particles under a critical value. The porous particles were mostly eliminated during crushing as well. Thus, sand stone coarse aggregate particles reduced in size and amount could not propagate micro cracking with in sound recycled coarse aggregate and into the other constituents of the recycled aggregate concrete subjected to freezing and thawing action.

2.1.11.3 Chloride diffusion/Penetration

Limbachiya et al. (2000) concluded that the use of 100% coarse RCA has no negative influence on the chloride diffusion of resulting concrete.

Olorunsogo et al. (2002) showed that chloride conductivity increased with increases in the replacement levels of RA for a given curing duration of concrete mixes. At a curing age of 3, 7, 28 and 56 days, the concrete mix that containing 100% RA showed 41.4, 53.6, 73.2 and 86.5% increase in the value of chloride conductivity over the mix that contained 0% RA, respectively. Considering the effect of curing age on the chloride conductivity of RA concrete, showed that the longer the duration of curing, the lower the conductivity of concrete mix at a particular replacement level of RA. For 0, 50 and 100% RA concrete, the mix that was cured for 56 days showed
69.0, 62.7 and 59.2% increase in chloride conductivity over the mix that was cured for 3 days, respectively. Comparing the recommended values of chloride conductivity for concrete durability classified by Alexander et al. (1999), the 100% NA concrete attained the class status of ‘good’ at the curing age of 56 days with a value of 1.48 mS/cm. 50% RA and 100% RA concrete mixes fall under the ‘poor’.

Otsuki et al. (2003) concluded that the chloride penetration increase with an increase in the water binder ratio. Furthermore, for the same water binder ratio the chloride penetration of recycled aggregate concrete are slightly higher than those of normal aggregate concrete. This is due to the presence of old ITZ and adhesive mortar in recycled aggregate, which makes recycled aggregate concrete more permeable than normal aggregate concrete. Decrease in chloride penetration of recycled aggregate concrete can be achieved by using the double mixing method in case of high water binder ratio concrete.

Shi Congkou et al. (2007) concluded that the resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, the resistance was improved by incorporation fly ash in the concrete mixtures. A decrease in the W/B ratio improved the resistance to chloride ion penetration. Further, it was found that the resistance increased as the curing age increased from 28 to 90 days.

Poon et al. (2007) concluded that Chloride ion penetration could be significantly minimized with a proper mix design. Concrete, which had a low w/c ratio and the use of fly ash as an addition of cement, had much better resistance to chloride ion penetration compared to that with high w/c ratio and without fly ash addition.

Ann et al. (2008) concluded that the rapid chloride ion test indicated that the concrete containing recycled aggregate forms a more open pore structure, compared
to control concrete specimens. The use of 30% pulverized fuel ash and 65% ground granulated blast furnace slag in binder resulted in a decrease in the charged passed through concrete specimens, which implies the enhancement resistance to chloride ions permeability in to a concrete body.

2.1.11.4 Carbonation

Rasheed Uzafar et al. (1984) concluded that concrete made with already carbonated recycled aggregate suffers 65% more of carbonation than conventional concrete.

Barra et al. (1998) demonstrated that the carbonation risk of recycled aggregate concrete using a higher amount of cement than 400 kg/cum of concrete mix is larger than in conventional concretes. The carbonation depth in recycled aggregate concrete and conventional concrete is similar when the amount of cement employed in the mix is between 300 kg/cum and 400 kg/cum. This occurs when the cement is added; the aggregates are saturated or very humid. In poor concrete, using less than 300 kg/cum of cement, the carbonation depth is similar in both concretes.

Sagoe-Crentsil et al. (2001) reported that the variation of depth of carbonation with time under accelerated exposure conditions is a parabolic rate law for coarse RCA concrete with OPC cement as with the reference mix. The coarse RCA concrete with slag cement shows a slight deviation from this trend, suggesting the possibility of a different mechanism of carbonation.

Buyle-Bodin et al. (2002) concluded that the process of CO2 diffusion in concrete with fine and coarse recycled aggregate complies parabolic rate law established with classic concrete. However, concrete with fine and coarse recycled aggregate was
carbonated faster than natural aggregate concrete. Extended curing of concrete made with fine and coarse recycled aggregate decreases the carbonation rate.

Zaharieva et al. (2003) showed that the replacement of natural aggregates by recycled aggregates affects the quality of the concrete cover. The carbonation of recycled aggregate (both coarse and fine aggregates) concrete (RAC) is faster. This effect limits the use of recycled aggregate in the production of reinforced concrete elements. Nevertheless, based on the criteria proposed in other studies, RAC can be characterized as being of moderate quality rather than poor quality. Mixed aggregate concrete is intermediate between RAC and NAC. It can be concluded that the main problems of durability are caused by the use of recycled sand. Therefore, the use of the fine recycled aggregate needs to be restricted. Another way of increasing the durability of RAC is to use extended curing using a moist environment.

Otsuki et al. (2003) concluded that the carbonation depth increase with an increase in the water binder ratio. Furthermore, for the same water binder ratio the carbonation depth of recycled aggregate concrete are slightly higher than those of normal aggregate concrete. This is due to the presence of old ITZ and adhesive mortar in recycled aggregate, which makes recycled aggregate concrete more permeable than normal aggregate concrete. Decrease in carbonation depth of recycled aggregate concrete can be achieved by using the double mixing method in case of high water binder ratio concrete.

Levy et al. (2004) concluded that the carbonation depth decreased when the replacement was 20 or 50% of coarse recycled masonry aggregate (CRMA) and coarse recycled concrete aggregates (CRCA). For CRMA concrete family, this better behaviour also occurred when the replacement ratio was 100%. This behaviour shows
that carbonation depth depends strongly on the chemical composition of the concrete and not only on the physical aspects.

### 2.1.11.5 Water Sorptivity

Absorption is regarded as the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. The capillary suction is dependent on the pore geometry and the saturation level of the material. The water absorption that is caused by wetting and drying of concrete is an important fluid transport mechanism near the surface, but becomes less significant with depth. The rate of movement of a wetting front through a porous material under the action of capillary force is defined as Sorptivity.

Olorunsogo et al. (2002) showed that water sorptivity increased with increases in the replacement levels of RA for a constant age of curing. At a curing age of 3, 7, 28 and 56 days, the concrete mix that containing 100% RA concrete showed 47.3, 43.6, 38.5 and 28.8% increases in the value of water sorptivity over the mix that contained 0% RA, respectively. It was shown that these percentage increments decreased with duration of curing, for a considerable curing length of time there was no difference in water sorptivity values.

### 2.1.11.6 Reinforcement corrosion

RasheedUzafar et al. (1984) concluded that rust occurs in the steel reinforcement with 2-3mm of clean cover at 2 months. The rust risk in reinforced recycled aggregate concrete is higher than conventional concrete. However this risk is possible to decrease with lower w/c ratio in recycled aggregate concrete the conventional concrete.
Limbachiya et al. (2000) concluded that little difference in the performance of the RCA and NA concrete mixes, suggesting equal corrosion activity. However, the corrosion currents of the steel in 100% coarse RCA concrete were slightly higher and the corrosion initiation time was shorter than concrete containing NA and up to 50% coarse RCA.

Ann et al. (2008) concluded that the chloride threshold level for steel corrosion was not affected by pulverized fuel ash (PFA) or ground granulated blast furnace slag (GGBS) as partial replacement for cement in binder, but the OPC concrete with only recycled aggregate indicated the lowest level of chloride threshold level. After the onset of corrosion, the corrosion rate was significantly reduced by PFA and GGBS, due to the restriction of cathodic reaction, which needs a sufficient supply of oxygen and water.

2.1.11.7 Creep, elastic shrinkage and drying shrinkage

Mesbah et al. (1999) concluded that for the recycled aggregate mortars the drying shrinkage reduces 15% when the metallic fibres are added and tiny changes when the polypropylene fibres are added.

Sagoe-Crentsil et al. (2001) reported that both natural and recycled aggregate concretes display similar trends with regard to the rate of shrinkage. The shrinkage strains associated with recycled concrete made with slag cement are over 35% higher and with Portland cement are over 15% higher than the reference mixture.

Shi Cong kou et al. (2007) concluded that the drying shrinkage of concrete increased with an increase in the recycled aggregate content. However, the use of fly ash as a partial replacement of cement was able to reduce the drying shrinkage of the
recycled aggregate concrete. Further, a decrease in the W/B ratio also led to a reduction in the drying shrinkage. The creep of the concrete increased with an increasing recycled aggregate content. The use of fly ash as a partial replacement of cement was able to reduce the creep of concrete as a result of the greater long term strength development due to the pozzolanic reaction of fly ash.

Poon et al. (2007) concluded that the use of low w/c ratio or fly ash as a addition of cement is a good way to reduce the potential high drying shrinkage of concrete prepared with recycled aggregate. Drying shrinkage of recycled aggregate concrete tended to decrease with an increase in compressive strength. Reducing w/c ratio from 0.55 to 0.40 was a more effective way to mitigate the drying shrinkage of concrete compared to adding 25% fly ash in the concrete mix.

Eguchi et al. (2007) concluded that as the replacement ratio of recycled coarse aggregate increases the drying shrinkage strain increases. However by estimating the decrease in quality by relative quality values and adjusting the replacement ratio, the quality required for the concrete can be ensured.

2.1.12 Economic Comparison Concrete Recycling

Eguchi et al (2007) proposed new production method for recycled aggregate concrete with different replacement ratios called as “On-site mixing method”. In this method, all the materials except the recycled coarse aggregate (base concrete) were first mixed at an available batching plant, and the mixture was transported by loading to a truck agitator. Next, the recycled coarse aggregate was measured using temporary weighing and loading equipment installed at the construction site, and was loaded to the truck agitator. The truck agitator drum was then rotated at a high speed and a
recycled coarse aggregate was mixed with the base concrete. The effectiveness of a production method for the recycled concrete is confirmed. When recycled concrete is produced by this method, the cost and the environmental loads could decrease in comparison to construction without recycling, at least in terms of large-scale construction, or construction with recycling to crusher run only.

Tam (2008) recommended that there should have standard specifications to encourage the implementation of recycled materials for non structural and structural application. One of the main burdens on the use of recycled materials is its low quality. Although there are literatures that to support high quality of recycled materials can be produced, the industry is still hesitated to use the recycled materials for new material production. It is encouraged that the government should widely initiate the use of recycled materials for their projects, which can then encourage its use to the industry. It should be highlighted that improving technology for producing recycled materials can significantly improve their quality. Lack of in house training on concrete recycling is another major issue affecting the use of recycled materials in the industry. It is encouraged that training programmes should be produced to all employees to enhance their environmental awareness, thus to improve the environment.

Tam (2008) concluded that the huge generation of construction waste has reached a state that a warning signal is flicking as reflected from the running out of landfill areas. One of the best ways to manage this acute environmental problem is by recycling construction waste. As concrete waste forms the major source of construction solid waste, recycling concrete waste is the best option to mitigate quantities of construction waste. And also studied the cost and benefit on the current
practice in dumping the construction waste to landfills and producing new natural materials for new concrete production, and the proposed concrete recycling method to recycle the construction waste as aggregate for new concrete production. With the advent of the cost on the current practice, it is found that the concrete recycling method can result in a huge sum of savings. The benefits gained from the concrete recycling method can balance the cost expended for the current practice. Therefore, recycling concrete waste for new production is a cost-effective method that also helps protecting the environment and achieves construction sustainability.

2.1.13 Structural Properties

The structural properties of recycled aggregate concrete are as follows.

2.1.13.1 Flexural behaviour of recycled aggregate concrete

Mukai et al. (1988) concluded that the failure in low reinforced concrete beam specimens made with recycled aggregate or conventional aggregate occurs when reinforcement yields. However in high reinforced beam specimens the failure occurs by compression of top part. On subjecting both the reinforced recycled aggregate concrete and conventional concrete beam specimens to the same load conditions it was discovered that cracking first appeared in the reinforced RAC beam specimens, however the ultimate load is similar in both beams with respect to low reinforced concrete beam specimens made with recycled aggregates the displacement is larger than in conventional concrete. However there is no difference when the specimens are strongly reinforced.
2.1.13.2 Shear behaviour of recycled aggregate concrete

Mukai et al. (1988) concluded that the shear strength of a low reinforced concrete beam specimen made with recycled aggregate is 10% lower than that of a conventional concrete beam. However with reinforcement, the recycled aggregate concrete beam specimens achieve the same and sometimes even larger strength than conventional ones. Recycled aggregate concrete beam specimens with low transversal reinforcement have less ductility than conventional concrete specimens. However this can change when the beam specimens are strongly reinforced.

Yagishita et al. (1993) concluded that in concrete beam specimens made with recycled aggregate the first diagonal crack occurs before than that of conventional concrete. However, the ultimate shear load is similar in both recycled aggregate concrete and conventional concrete beam specimens. The cracks widths are larger in recycled aggregate concrete beam specimens. The bond between reinforcement and concrete is lower in recycled aggregate concretes than in conventional concrete. The splitting crack is more relevant in recycled aggregate concretes than conventional ones, however this phenomena is less significant with the presence of transversal reinforcement.

Gonzalez-Fonteboa et al. (2007) concluded that little differences were observed in the structural behavior of concrete beams in terms of both deflections and ultimate load. Differences were only evident during the analysis of cracking. Premature cracking and notable splitting cracks along the tension reinforcement were observed.
in recycled concrete beams. Both may be controlled by introducing stricter limits on the minimum stirrups spacing.

2.1.13.3 Compression behaviour of recycled aggregate concrete

Yang et al. (2006) concluded that the typical failure modes of RACFST columns are similar to those of the normal CFST columns. They were all overall buckling failure. The ultimate capacities of such composite columns decreased with the increase in load eccentricity ratio. The recycled aggregate concrete in-fill columns have slightly lower but comparable ultimate capacities compared with the specimens filled with normal concrete. It was found that, in general, the ultimate capacities of the members with normal concrete were 1.7 to 9.1% higher than those of circular columns with recycled aggregate concrete containing 25% recycled coarse aggregate and 50% recycled coarse aggregate, and for square specimens, the ranges are 1.4 to 13.5%. The lowering in capacities of RACFST columns can be attributed to the lower strength of recycled aggregate concrete as compared to the normal concrete. Generally, ACI, AIJ, AISC-LRFD, BS and DBJ methods are conservative for predicting the strengths of circular and square composite columns filled with recycled aggregate concrete. However, EC method gives a member capacity about 5 and 12% higher than the experimental result for circular and square RACFST columns respectively, and gives an unsafe prediction.

2.1.13.4 Bond behavior of recycled aggregate concrete with steel rebar’s

Xiao et al. (2007) concluded that the shape of the load versus slip curve between recycled aggregate concrete and steel rebars is similar to the one for normal concrete and steel rebars, which includes micro slip, internal cracking, pull out, decending and
residual stages. Under the conditions of the equivalent mix proportion and compared with that of normal concrete, the bond strength between the recycled aggregate concrete and the plain rebar decreases by 12% and 6% for an RCA replacement percentage of 50% and 100%, respectively. While the bond strength between the recycled aggregate concrete and the deformed rebar is similar, irrespective of the RCA replacement percentage. For the case of the same compressive strength, the bond strength between the recycled aggregate concrete with 100% replacement of RCA and steel rebars is higher than the one between the normal concrete and steel rebars. For the recycled aggregate concrete, the bond strength between deformed steel rebars and concrete is approximately 100% higher than the one between plain steel rebars and concrete, and the coefficient of variation for the bond strength of the plain steel rebar is much higher than the one for the deformed steel rebars. The anchorage length of steel rebars embedded in the recycled aggregate concrete with 100% replacement can be chosen as the same for normal concrete under the condition of the same compressive strength of concrete.

Eguchi et al. (2007) studied that when the lateral reinforcement ratio is high, the maximum bond stress tends to decrease slightly as the replacement ratio of recycled aggregate increases. The bond failure strength of recycled concrete can be evaluated as being safe according to the AIJ formula in the standard specification, regardless of its replacement ratio.

### 2.1.13.5 Seismic performance of recycled aggregate concrete

Xiao et al. (2006) concluded that the presence of RCAs reduces the yield, maximum and ultimate loads of frames made with RAC; however, this reduction is
less than that of the mechanical properties of the RAC material. The characteristic
displacements among the test specimens prove that there are no obvious differences
between frames with recycled concrete and conventional concrete, particularly from
the ductility coefficients and lateral rotations points of view. From the hysteresis
loops, the energy dissipation and the rigidity degradation points of view, the seismic
performance of frames with recycled aggregate concrete is comparable to that with
conventional concrete. It is also concluded that the frames with properly mix-designed
recycled aggregate concrete are good enough to resist an earthquake according to GB
code, and it is feasible to apply the recycled aggregate concrete structure in civil
engineering.

2.1.13.6 Glass fiber reinforced recycled aggregate concrete

Prasad et al. (2007) concluded that recycled aggregate concretes are not inferior to
normal concrete. Addition of glass fibers has definitively increased the compressive
strength, though marginally in the range of 2 to 3%. The addition of glass fibers in the
recycled aggregate concrete has increased the split tensile strength by 13.03 and
10.57% in M20 and M40 grade concretes and also the flexural strength has increased
by 10.62 and 7.94% in M20 and M40 grade of concretes. There is an improvement in
younsgs modulus value with glass fibers addition in both normal and recycled
aggregate concrete. The increased strains at constant stress in glass fibrous concretes,
indicates improved ductility and energy absorption capacity.

Ghorpade Vaishali G et al. (2012) concluded that the compressive, tensile,
flexural and shear strengths of fibre reinforced high performance recycled aggregate
concrete mixes increased with the increase of fiber content up to 1% and decreased
beyond 1% fiber volume fraction. Balling of fibers at 1.25% volume fraction is mainly responsible for reduction in strengths. Maximum compressive, tensile, flexural and shear strengths are achieved at 1% fiber volume for steel, glass and polypropylene fibers. The percentage increase in strengths due to addition of fibers, is observed more in mixes prepared with recycled aggregates than those prepared with natural aggregates. The chloride ion permeability of mixes prepared with recycled aggregates is higher when compared to corresponding mixes prepared with natural aggregates.

2.1.14 Artificial Neural Networks and Fuzzy Logic

Topcu et al. (2008) studied the models in artificial neural networks and fuzzy logic systems for predicting compressive strength and splitting tensile strengths of recycled aggregate concretes containing silica fume.

2.1.15 Conclusions

From the mid seventies onwards the properties of recycled aggregates and their applications have been studied throughout the world. The conclusions obtained from the research and investigations carried out are as follows;

1. The recycled aggregates obtained from crushed concrete consist of adhered mortar and original aggregates. The quantity of adhered mortar in recycled aggregates is higher in small size aggregates. Due to the adhered mortar in original aggregates mechanical and physical properties of recycled aggregates are worse than those of raw aggregates. Recycled aggregates properties: density, absorption, porosity, Los Angeles abrasion, freezing and thawing resistance are inferior in quality those of raw aggregates.
2. According to RILEM recommendations, the recycled aggregates obtained from crushed concrete, should be defined as type II. Type II is a material that originated primarily from concrete rubble. The recycled aggregate must have a lower than 10% water absorption capacity and a minimal dry particle density of 2000 kg/m$^3$. Recycled aggregate concrete is allowed to achieve 50/60 MPa. It does not require an additional test to be used in exposure class 1. In order to use in other exposure classes ASR expansion and bulk freeze-thaw test are required.

3. The water absorption capacity of recycled aggregates has to be taken into account when using recycled aggregate in concrete production. The recycled coarse aggregates used in concrete manufacture should be kept in humid conditions. This will ensure not only concrete’s workability but also the effective w/c ratio. If the recycled aggregates are used in this condition the new interface transition zone can be effective, producing better properties, and prevention to freezing and thawing. The new interfacial transition zone also depends on the concrete production process. Although it is not possible to improve the old interface transition zone it is possible to achieve an effective new transition zone which produces a low w/c ratio cement paste on the interface.

4. In concrete made with 100% of recycled coarse aggregates the effective w/c ration must be lower than that of conventional concrete in order to obtain the same compression strength. Therefore, in recycled aggregates concretes (using more than 50% of recycled coarse aggregates) more cement than conventional concretes is necessary to achieve the same workability and compression strength.
5. The compression strength of recycled aggregate concrete depends on the strength of the original concrete. The adhered mortar of recycled aggregates can be the weakest point in the concrete.

6. There is not a significant change in the properties of concrete made with 20-30% of recycled coarse aggregates with respect to that of conventional concrete.

7. Concretes made with 50 and 100% of recycled aggregates strength have a lower increase in compression strength from 7 to 28 days than those of conventional concrete employing only raw aggregates.

8. The variation coefficient of recycled aggregate concrete is higher than conventional concrete.

9. The tension strength of concrete made with recycled aggregates and natural sand is similar to conventional concrete. However, if recycled aggregates are saturated at concrete production, the tension strength of recycled aggregate concrete decreases.

10. The modulus elasticity of recycled aggregate concrete is always lower than conventional concrete.

11. Concrete made with recycled aggregates needs to have a lower effective w/c ratio to achieve lower permeability.

12. The freezing and thawing resistance is lower in recycled aggregates concrete than in conventional concrete. However it can be improved if the recycled aggregates are humid and the air-entrained is used at concrete production.

13. A lower w/c ratio can improve rust risk in recycled aggregate concrete, decreasing its permeability.
14. The rubble processed at recycling plants may originate from structures which were attacked by ASR or which were potentially reactive, but did not react due to a lack of favorable conditions (such as humidity). Preventive measures such as the use of low alkali Portland or blast furnace slag cement, may increase the durability of the recycled concrete as far as ASR is concerned.

15. The first cracking load is lower in recycled aggregate concrete specimens than that of conventional concrete.

16. According to flexure and shear behavior, the ultimate load is similar in reinforced recycled aggregate concrete specimens and conventional concretes.

17. The bond resistance in recycled aggregate concrete is lower than that of conventional concrete.

2.2 LITERATURE REVIEW OF SLAB ELEMENTS

Aron Zaslavsky (1967) presented a yield line analysis for simply supported rectangular concrete slabs (isotropically reinforced) with central rectangular openings, under uniformly distributed load. The three possible yield line patterns (mechanisms) are analyzed and design diagrams were derived for rapid determination of the correct mechanism and the required ultimate moment. Numerical examples are also provided.

Gene Corley and Neil. M. Hawkins (1968) reported the tests on concentrically loaded slab–column specimens containing either lightweight or normal weight aggregate concrete and shear-head reinforcement made from structural shape. Based on the results of tests on 21 specimens, a design procedure for shear-heads at interior supports was proposed and a design example was presented. Strengths implied by this design procedure were compared with measured loads from other tests. The proposed design procedure was shown to provide shear capacity in the slab that is consistent
with load factors and strength reduction factors being considered for use in the 1970 ACI Building Code.

Aron Zaslavsky and Chaim H Avraham (1970) presented a yield line design for rectangular balconies fixed along two adjacent edges and subjected to uniformly distributed load. Full scale tests of 10 slabs (with varying span and reinforcement ratios) confirmed the correctness of the predicted collapse mechanisms, the actual collapse loads being higher than the predicted ones due to membrane action. The proposed design method includes deflection control by specifying minimum depth.

Adrian E Long (1975) presented formulae for isotropically reinforced square slabs supported on square columns. Application to relevant test results reported in the literature indicated that the formulae represent a significant improvement over previous methods which are largely empirically based.

Coull and Hag (1975) presented the results from a series of tests on small scale models to determine the effective bending stiffness of floor slabs coupled shear walls. The experimental results indicate the relative influence of the dimensions and shape of the walls (plane walls, flanged walls, and box cores), wall spacing, and slab dimensions on the effective width and stiffness of the connecting slab.

Jacob S Grossman (1980) described approximate simplified procedure for estimating the effective moment of inertia $I_e$ for beams, T-beams or one way slabs constructed of normal weight aggregate concrete or lightweight concrete, reinforced with 40-80 ksi reinforcing bars. The results are compatible with $I_e$ values obtained from Eq. (9-7) of ACI 387-77. The proposed simplified equation does not require computations of moment of inertia of the cracked section.
Ibrahim et al. (1988) carried out an experimental program on axisymmetric reinforced concrete slabs to estimate the punching shear resistance. He proposed a model to estimate the punching resistance. The proposed model can estimate the punching shear behaviour beyond the cracking stage and also the flexural strength capacities. The results are compared with codes of ACI and BS 8110.

Clark et al. (1990) studied the punching shear resistance of light weight aggregate concrete slabs. In the punching shear study the light weight aggregates (oven dry density $<2000$ kg/m$^3$) of Lytag, Pellite, Leca, Fibo and Liapor were taken. The normal weight aggregates which were obtaining from Thames Valley (U.K) were taken as reference for comparison of results. In the experimental study the design densities of the materials tested ranged from 85% to 65% of that of normal weight concrete. Relative to their densities, the light weight aggregate concretes were upto 30% stronger in shear than those made with the reference aggregate.

John et al. (1990) investigated about the punching shear strength of reinforced concrete slabs with varying span-depth ratios. For the experimental study, ten axisymmetric slabs were tested. Out of ten five were with flexural reinforcement and five were with both flexural and shear reinforcement. The slab thickness was kept constant. During the experimentation, the supporting diameter was varied to produce different span-depth ratios. Based on the experimental study the authors concluded that for reinforced concrete slabs of constant thickness, the punching shear strength increases as the span to depth ratio decreases below 6. The strength increases may be due to the development of compression struts forming an arch mechanism in the slabs and in-plain compressive force resulting from the friction at the support. The addition of shear reinforcement had a significant effect on the punching shear strength of the
slab specimens. The slab with shear reinforcement showed more ductile behavior than those specimens without shear reinforcement. Excellent anchorage of shear reinforcement greatly enhanced the shear strength of the specimens with large span-depth ratios. The authors observed that the shear reinforcement was less effective in the specimens with a span-depth ratio of 2 due to steeper failure cracks. The observed punching shear strengths were much greater than the values permitted by the ACI building code (ACE-318-83). This was especially true for the specimens with shear reinforcement and with small span-depth ratio.

Gilson et al. (1992) conducted experimentations on beam-column-slab connections for evaluation of joint shear. Basically during strong earthquake, beam-column-slab connections can experience severe reversed cyclic loads. If the joints in a moment-resisting frame do not possess adequate strength, the overall strength and stiffness of frame may get adversely affected. The ACI building code and ACI-ASCE committee recommendations for design of beam-column connections were developed primarily from the results of tests conducted on specimens constructed with concrete strength less than 600 psi and nominal yield strength of 60ksi or less. But the authors conducted tests with concrete having compressive strengths greater than 12000 psi and with yield stress of steel 75 to 85 ksi. Based on the experimental observations, they concluded that the joint shear strengths are higher than ACI 318 and ACI 352 design recommendations.

Kuang and Morley (1992) reported the Punching shear tests on 12 restrained reinforced concrete slabs. The slab panels were supported and restrained on all four sides by edge beams. The influence of the degree of the edge restraint, percentage of steel reinforcement, and span depth ratio of the slabs on the structural behaviour and
punching shear capacity of the slabs was studied. They observed that the punching shear strength was much higher than those predicted by Johnson’s yield line theory, BS 8110, and ACI 318. The enhanced punching shear capacity was a result of compressive membrane action caused by restraining action at the slab boundaries.

Desayi et al. (1992) proposed a method to determine the span to effective depth ratios of simply supported (as well as continuous) rectangular concrete slabs. In this method they computed the total deflection of the slab as the sum of the short-term deflection and long term deflection. The calculation of shor-term deflections proposed by Desayi depends on the value of deflection coefficient which is given by Timoshenko and Krieger (1959). However, in Timoshenko and Krieger the value of deflection coefficient is given for one condition only. The design charts presented by Desayi are suitable to different conditions.

Kuang Fang et al. (1994) reported the behavior of 18 partially restrained reinforced concrete slabs with isotropic reinforcements under concentrated load. The primary variables included concrete strength, grade of steel reinforcement, thickness of slab, and the degree of fixity at support. Test results indicated that all the slabs finally failed by punching. The key elements determining the load capacity of thick slabs (115mm) were concrete strength and thickness. The amount of steel did not significantly affect the load capacity, whereas for thin slabs (75mm), the load capacity was primarily dominated by flexural capacity. Slabs having lower reinforcement content exhibited greater intensity and longer existence of the state of compressive membrane action if they had the same span-to-depth ratio and thickness.

Nasser Meamarian et al. (1994) described an approach to consider the effects of compressive membrane forces in the analysis and design of pre-stressed and/or
reinforced concrete one way members. The theory of plasticity was applied to find the ultimate load and support reactions for a one way restrained edge slab strip or beam. Modified compression field theory was used in the next step to relate the sectional forces to internal stress, strain, and angle of diagonal cracking at each specified location and to the total deflection. Numerical methods were used in developing a computer program to perform the calculations. The output for 16 one-way strips is compared with test results. Reasonable agreements are found for load, deflection and support reactions at the ultimate load conditions.

Neil Hammil and Amin Gali (1994) have conducted experiments on corner slab-column to know the behaviour of punching shear resistance. The experimentation was performed on five full scale reinforced concrete flat-plate connections with corner columns subjected to shear-moment transfer. In the experiment, the variable parameters were amount of shear reinforcement and loading procedure. The design procedure in the ACI 318-89 code and Canadian standard Can3-A-23.3-M84 was discussed. They observed that the equations suggested in those codes were conservative and need improvement.

Hideaki Saito et al. (1995) reported the loading capacities, deformations and failure modes of various types of reinforced-concrete structures subjected to loads applied at various rates. Flat slabs, slabs with beams and cylindrical walls were tested under static, low speed and high speed loading. FE (finite element) analysis was applied to estimate the test results using a layered shell element. The analysis closely simulated the experimental results until punching shear failure occurred.

James Hurst and Gamel Ahmed (1998) presented a computer model to predict the thermal response of carbonate and siliceous aggregate (normal weight) concrete slab
specimens subjected to fire. Validation of the model was based on data collected during comprehensive fire test programs conducted by the Portland cement association in the 1960s. The model's ability to replicate the experimental results with good agreement substantiates it as a valuable analytical tool for research and design applications related to concrete fire behavior.

Marzouk et al. (1998) tested the slab-column connections under combinations of gravity and lateral loads to investigate the effect of using high-strength concrete slab on the structural behavior of the slab-column connections. The variables selected for this study were the strength of concrete slab, the flexural steel reinforcement ratio, and the moment to shear ratio. As the concrete slab strength increases from 35 to 75 MPa, the shear strength increases by 7%. The use of high-strength slab has a significant effect on the load-deflection characteristics for specimens subjected to high-moment. The ultimate deflection increases and the failure mode become less sudden and more gradual, if high-strength concrete slab is used. The first yielding for specimens constructed with high-strength concrete slab occurs at loads considerably lower than those for specimens constructed with normal strength concrete. The radius of yielding significantly increases for specimens constructed with high-strength concrete slab, therefore, the steel reinforcement is utilized better and a much more desirable steel stress distribution is produced in the area around the column by the use of high-strength slab.

Mary Beth Hueste et al. (1999) developed a model for predicting the punching shear failure at interior slab-column connections based on experimental results obtained from previous researchers. A four storey frame office building that experienced punching shear failure during North bridge earthquake was evaluated
using this model and the occurrence of punching shear failure was successfully post calculated for the ground motion recorded nearest the structure. The study building was evaluated for three ground motions scaled to the same peak ground acceleration. The building response varied for each record, but in general, it was found that the inclusion of punching shear failure can modify the overall building response in terms of drift, fundamental period, inelastic activity and base shear distribution. In case of the study building, the presence of the stiffer moment-resisting perimeter frames helped limit the magnitude of the effect that the punching shear failure had an overall structural response.

Alaa and Walter (2000) presented the experimental program as well as the test results related to the flat slabs and shear strength of slab column connections. Based on the test results, the shear strength of slab-column connections in a real slab system with realistic boundary conditions was assessed. The results were compared with the latest provision of ACI, and with a proposed shear strength equation.

Manuel Alvarez et al. (2000) presented the results of bending tests on three continuous reinforced concrete slab strips and compared them with calculations according to linear, nonlinear, and limit analysis approaches, as well as with ACI 318 code. It is demonstrated that the reduced ductility properties of cold-deformed and coiled small-diameter reinforcing bars and wires may result in dangerous strain localizations, impairing rotation capacity, permissible moment redistribution, and ultimate strength. A nonlinear analysis method for refined deformation investigations is presented and minimum ductility requirements for reinforcing steel are suggested.

Osman et al. (2000) studied the behavior of high strength light weight concrete slabs under punching loads. In this study, six slabs were tested under central load.
Four slabs were constructed with high strength light weight concrete of compression strength less than 70MPa, with steel ratio ranging from 0.5 to 2.0%. Two reference specimens were constructed with normal strength concrete and light weight aggregates and had steel reinforcement ratios of 1 and 0.5%. From experimental results they concluded that specimens with a reinforcement ratio of 0.5% failed under flexure, while concrete specimens with a steel ratio of 1.0% failed under punching shear with some ductility and concrete specimens with reinforcement ratio > 1.0% failed under punching shear. The ductility of high strength light weight concrete slabs decreases as the tensile steel ratio increases. Doubling the steel reinforcement ratio from 0.5 to 1.0% decreased the ductility by 23%, while increasing the ratio from 0.5 to 2.0% decreased the ductility by 48%. The ductility of high strength light weight concrete slabs (HSLW) was higher by 27% than the ductility of normal strength normal weight concrete slabs (NSNW) with a steel ratio of 0.5%. For specimens with a steel ratio greater than or equal to 1.0%, the ductility of HSLW and NSNW were almost equal. The angle of failure of HSLW concrete slabs failed in punching ranged from 25 to 29 degrees. The angle ranged from 26 to 30 degree and from 32 to38 degree for NSNW and HSNW concretes respectively.

Hock C Tan et al. (2001) examined the use of ordinary steel and concrete strain gauges to monitor the dynamic response of reinforced concrete (RC) slabs excited in non-destructive vibration testing. Plots of measured dynamic strains in the embedded steel reinforcement bars and on the concrete surface, as well as of mid-span deflection, are presented at different levels of load-induced damage. The plots show unique strain and deflection signatures that vary with the internal state of the slab and could be used for condition monitoring and residual strength identification. It is
feasible that the techniques outlined could be used in AI-based evaluation tools for RC slabs and other RC structures.

Mikael Hallgren and Mats Bjerke (2002) conducted a non-linear finite element analysis of punching shear failure of column footings. The authors felt that the current design methods and code formulas for the assessment of the punching shear strength are normally based on tests on slabs with relatively high slenderness i.e. with higher shear-span to depth ratios. Column footings normally have low shear-span to depth ratios. Earlier punching tests on column footings indicate that the failure mechanism for punching slabs with low shear-span to depth ratios differs from that of slab with high shear-span to depth ratios. The study also confirms that the punching shear strength of the analyzed slabs strongly depend on the compressive strength of concrete.

Menetrey (2002) presented a synthesis of punching failure in reinforced concrete. Experimental results were presented to show the difference between flexural and punching failure. The punching failure mechanism is discussed based on results obtained with numerical simulations demonstrating among others the influence of the concrete tensile strength. Using these results, an analytical model is derived for punching load prediction. The model allows a unified treatment of slabs with various types of reinforcement.

Theodarakopoulos and Swamy (2002) presented a simple analytical model to predict the ultimate punching shear strength of slab-column connections. The model is based on the physical behaviour of the connections under load and therefore applicable to both light weight and normal weight concrete. The model assumes that punching is a form of combined shearing and splitting, occurring without concrete
crushing but under complex three dimensional stresses. Failure is then assumed to occur when the tensile splitting strength of the concrete exceeded. The theory is applied to predict the ultimate punching shear strength of 60 slab-column connections reported by earlier researchers. The results show very good agreement between the predicted and experimental values. The uniqueness of the model is that it incorporates many physical characteristics of the slabs and their failure behaviour and this is reflected by its ability to predict extremely well the results of tests conducted by earlier researchers.

Antonio et al. (2003) computed the response of clamped slabs when subjected to spatially sinusoidal harmonic line loads using Boundary Element Method (BEM). Frequency and time responses have been computed for slabs with and without lateral confinements for different thickness and varying spatially sinusoidal harmonic line loads.

Pilakoutas and Lix (2003) studied about the validation of a patented shear reinforcement system for reinforced concrete flat slabs. The system called shear band consists of elongated thin steel strips punched with holes which undulate into the slab from the top surface. The advantage of the new reinforcement system is structural effectiveness, flexibility, simplicity and speed of construction. The slabs reinforced in shear exhibited ductility behaviour after achieving the full flexural potential, thus proving the effectiveness of the new reinforcement. The results were compared with ACI 318 and BS 8110 codes, which confirm that the system enabled the slabs to avoid punching shear failure and achieve their flexural potential. Both codes are shown to lead to conservative estimates of flexural and punching shear capacities of reinforced concrete slabs.
Salim and Sebastian (2003) conducted an experimental study of the ultimate punching load capacity of reinforced concrete slabs restrained by means of incorporating hoop reinforcement. Four reinforced concrete slabs with one control specimen were tested to failure. In addition, the application of plastic theory for prediction of punching shear failure loads in restrained slab is presented. The predictions are in good agreement with a wide range of experimental data of earlier researchers.

Baskaran and Morley (2004) developed a new experimental method to test flat slabs with simple uniform loading with improved boundary conditions. A new form of punching shear reinforcement which will increase the punching shear resistance without affecting the flexural resistance is used. Available experimental methods to test flat slabs are revived to demonstrate the simplicity of the new approach. To show the effectiveness of the both the method and shear reinforcement, some experimental results are included. In the design of slabs in addition to self-weight, a uniform imposed load is usually considered. But in the laboratory, applying this uniform load is challenging. This is further complicated by the requirements to maintain proper boundary conditions. One way adopted in the past was testing multi panel slabs with multiple point loads. However, this is an expensive approach. Therefore, in this paper a very simple approach to test isolated flat slab panels with improved boundary conditions is presented. A special vacuum rig was constructed at Cambridge University engineering department. Details of the vacuum rig and some experience from experiments were presented. The method seems promising.

Ehab EI-Salakawy et al. (2004) reported the test results of seven full scale reinforced concrete slab-column edge connections strengthened against punching shear. In this study, three slabs contained openings in the vicinity of the column and the other four were without openings. The dimensions of the slabs were 1,540 x 1,020
x 120 mm with square columns (250 x 250 mm). The openings in the specimens were square (150x150 mm) with the sides parallel to the sides of column. The slabs were reinforced with an average reinforcement ratio of 0.75%, except for the two reference slabs. Two different strengthening techniques were considered. Based on the test results, it is concluded that the presence of FRP sheets and steel bolts substantially increase the punching capacity of the connection.

Kumar et al. (2004) analyzed the reinforced concrete rectangular slabs for different boundary conditions with corner opening by yield line theory. The ratios of the corresponding lengths of the sides of the opening and the slab are kept the same and the size of opening up to half of the length of the slab is considered. The ratio of the span moments to support moments is kept equal to 0.75. The design tables and the examples to explain the use of the tables for analysis of slab are presented.

Kwan (2004) developed a new yield line method that can be applied to any convex polygonal-shaped slab. In this method, the deflections of the slab regions divided by yield lines are measured in terms of the dip and strike angles of the slab surfaces which can define the geometry of all kinematically admissible collapse mechanisms or yield line patterns. The external work done and the internal energy dissipation at yield lines are evaluated as functions of the dip and strike angles and the principle of virtual work is used to determine the corresponding load factor. The final solution is obtained by minimizing the load factor with respect to the dip and strike angles. A computer program to implement this method was also presented.

Oliveira et al. (2004) reported the punching shear resistance of high strength concrete slabs with rectangular supports and three different load patterns. Prabhat Kumar and Rajesh Deoliya (2004) found that the finite difference method is very
slabs to simultaneously satisfy the condition of bending and the serviceability is presented. Design charts are provided allowing practical application of this method to enable the design engineer to adjust the steel reinforcement and depth. Design charts are also provided to find out effective depth when the area of steel to resist the bending is just adequate for deflection criteria.

Susanto Teng et al. (2004) summarize the research program on flat plate structures conducted jointly by the Nanyang Technological University (NTU) and the Building and Construction Authority (BCA) Singapore. The paper focuses on the punching shear strength of slabs with openings and supported by rectangular columns. Twenty slab specimens were tested under concentrated loads and it was found that the stresses in the slabs were concentrated mostly around the shorter sides of the rectangular columns. Openings reduce punching strength considerably and if the use of an opening is unavoidable, the best place for the opening is along the longer side of the column.

Umesh Dhargalkar (2004) derived a closed form solution for designing a simply supported one way slab loaded by a strip load along the span. Young-Ju Kim et al. (2004) investigated the contribution of the slabs and the effects of three types of retrofit methods. The test result indicated that the strains near the bottom flange of the composite beam connections were several times larger than those of the bare steel beam connections, resulting in a higher potential of fracture. Therefore, the slab effects are detrimental to the seismic behavior of the connection and should be considered in the design.

Gilbert and Guo (2005) described the experimental program of long-term testing of large-scale reinforced concrete flat slab structures. The results from test on seven
continuous flat slab specimens are presented. Each specimen was subjected to sustained service loads for periods up to 750 days and the deflection, strains, extent of cracking and column loads were monitored throughout. The measured long-term deflection is many times the initial short-term deflection. This effect is not accounted for adequately in the current coded approaches for deflection calculation and control. The results form a benchmark set of data from which more reliable deflection calculation procedures can be developed and calibrated.

Sudhakar and Goli (2005) presented the limit moment coefficients for trapezoidal reinforced concrete balcony slabs by using virtual work equations. Ian May and Sarosh H. Lodi (2005) examined the implications of current methods (Yield line analysis, Hillerborgs and Wood-Armer equations) to slab design. They reported that the sandwich approach method proposed by Morely, combined with the Clark – Nielsen equations is more conservative the other current methods.

Martin Lemieux et al. (2005) presented the results of comprehensive experimental investigation to assess the suitability of using thin bonded concrete overlays as an effective rehabilitation technique for concrete bridge decks. Nine 3.3 x 1.0 x 0.2m reinforced concrete slab panels with various configurations and different types of repair concrete were investigated.

Papanikolaou et al. (2005) presented results from an extensive testing programme involving a total of 3 reinforced concrete slabs with and without shear reinforcement subjected to a concentrated load in the middle. Shear reinforcement consists of either bent-up bars or closed stirrups. Measured punching shear strengths were compared with strengths predicted from two major design codes (the American, ACI 318 and the European Eurocode2) as well as from two models from the literature, the plasticity
model and a multi parameter empirical model. It was found that predictions by both codes were conservative in the case of slabs without shear reinforcement. Euro code 2 and ACI 318 predictions are generally similar in this case. Less conservative predictions were found in the case of slabs with shear reinforcement, particularly in the case of Euro code 2 that overestimated measured strengths of slabs with stirrups. The plasticity model tended to overestimate punching strength whereas the multi-parameter empirical model gave the best overall predictions. Finally bent-up bars appeared to be more efficient than stirrups in increasing the punching shear strength.

Subramanian (2005) reviewed the existing punching shear formula of IS 456 code. Basically the existing punching shear formula does not consider the effect of reinforcement in calculating the punching shear strength. The author of this paper has proposed the formula to estimate the punching shear strength with consideration of reinforcement ratio. The proposed formula is also verified with recent past experimental data which were given by the earlier researchers.

Aurelio Muttoni (2008) concluded the punching shear strength is a function of the opening of the critical shear crack in the slab. Its influence is assumed to be proportional to the product of the slab rotation times the slab thickness and corrected by a factor to account for the maximum diameter of the aggregate. This failure criteria simultaneously determines the punching load and the rotation capacity of the slab and thus of its ductility. The punching load can be determined by applying the failure criteria and a load rotation relationship obtained from a non linear analysis of the slab in bending. For axi-symmetric cases an analytical formulation derived on the basis of in non-linear moment curvature diagram. Size effect on the punching shear strength is accounted in the failure criteria of the critical shear crack theory. This effect, in
combination with the slenderness effect on the load rotation relationship proposed and can be formulated as a function of the span of the slab. ACI 318 doesn’t only exhibit a very large COV (coefficient of variation) when compared with test results, but it doesn’t include important effects, which leads to unsafe design in particular for thick and/or slender slabs with low reinforcement ratios.

Jahangir Alam et al. (2009) conducted experimental investigation of edge restraint on punching shear behavior of RC slabs. A total model of 16 model slabs with restrained and unrestrained edges have been tested in an effort to ascertain the influence of boundary restraint, thickness of the slabs on their structural behavior and punching load carrying capacity. Edge restraint has been provided by means of edge beams of various dimensions in order to mimic the behavior of continuous slabs. The cracking pattern and load deflection behavior of the slabs tested have also been monitored closely.

Stefano Guandalini et.al. (2009) confirmed that, due to size effect, the punching strength decreases with increasing slab thickness. At the same time, the deformation at failure decreases. For thick slabs with low reinforcement ratios, ACI 318 is low conservative. The coefficient of variation of the tests is fairly large as well. And also demonstrated that the failure criterion of the critical shear crack theory is applicable both for slabs with and without significant plastic deformations in the flexural reinforcement.

From the review of literature presented in this chapter, it can be observed that there is huge potential for the use of recycled aggregates in the production of structural concretes of different grades. Though a lot of research is going on recycled aggregate concrete, very little research is reported on the behavior of different
structural elements produced with recycled aggregates. Slabs are very important structural elements. Very little research is reported on the punching shear and flexural behavior of slab elements produced with recycled aggregates. Accordingly, the present investigation aims to study the punching shear and flexural behavior of slab elements produced with recycled coarse aggregates.