1.1 Significance of Research

Concrete is the most widely used construction material in the world with annual consumption estimated between 21 and 31 billion tonnes (Sabnis, 2012). Concrete is used more than any other man-made material (Lomborg, 2001) and is the second largest material consumed by mankind after food and water (Adegbola and Dada, 2012). Mehwish et al., 2013 have inferred that about 7.5 billion cubic meters of concrete is produced each year, more than one cubic meter for every person on the Earth. Production of concrete requires a host of material resources in terms of cement, sand and aggregates. Most of these materials used in concrete are naturally occurring and due to their extensive use are becoming scarce. River sand sources are fast depleting and the quantity of sand required is falling short of demand. To overcome this deficit, alternative material to river sand, namely manufactured stone crushed sand is being used in the industry in making concrete. It is well known fact that even aggregates are depleting and an alternative resource needs to be recognized and tried. The Countries who have faced with issues pertaining to shortage of supply of raw materials have already switched on to recycling for meeting their requirement. As a large proportion of this requirement can be supplemented by using the demolished material, nevertheless this secondary material needs to be assessed before being used in making of second generation concrete. This work tests such demolished material as an alternative material to be used in concrete by recycling thus saving onto the natural resources and also satisfying the social and environmental objective.
1.2 Background

1.2.1 International Scenario

The recycling industry had its existence in European countries way back during the Second World War. During this period a large quantity of rubble left behind was required to be disposed off. With the economy of these countries dismally shattered, acute transportation problem and shortage of equipment to work in aggregate quarries, the problem of reconstruction in these countries posed a major challenge. This paved a way in reusing of demolished concrete and building rubble as an alternate raw material. In addition to this, number of European countries notably, Germany, England, and Netherlands made systematic attempts to harness the use demolition material in the pavements.

Around the year 1973, fresh upsurge in research interest was seen in Western Europe and U.S.A. The objective of research this time was different: heavy urbanization and expansion had depleted the natural resources. Growth was seen consistently in the construction sector which resulted in heavy demand for these natural resources that was expected to grow further in future.

As reported by Van, 2006 the construction spending has increased from 3500 billion US Dollars in 2003 to 4800 billion US Dollars in 2008 and 6200 billion US Dollars in 2013. These figures indicate an enormous growth worldwide in construction market that is predicted to almost double in 10 years time.

A large demand for the natural resources must be met with to sustain the growth. Keun-Hyeok Yang et al., (2008) have reported that the global requirement of normal aggregates will be around 8 - 10 billion tons annually beyond 2010. Thus globally enormous need for natural non-renewal resources is required to satisfy this growth in the construction sector.
On account of the non-replenishing material the cost of construction is also considerably rising, thus paving way for a search of an alternative resource. Furthermore, major repair and renovation works have generated large amounts of waste adding to the burden for need of alternative method of disposal.

Lauritzen (2004) has reported that the quantity of construction and demolition waste discarded every year in the USA is about 250-300 million tonnes per year, 200 to 300 million tonnes in the European economic communities, 4.5 million tons annually in Egypt (Al-Ansary et al., 2004) 30 million tonnes in Japan and in the United Kingdom, and 24 million tonnes in France (Alaejos et al., 2004). It is estimated that these figures will increase nearly threefold by the turn of this century.

Evidently, these countries for the above reasons took up “Recycling Technology” very seriously. Significant research progress in the United States of America, the United Kingdom, Germany, France, Japan and Netherlands indicated positive and encouraging conclusions advocating utilization of recycled aggregate for construction purposes, especially for pavements of all types. Owing to the extensive studies, developed countries like the Netherlands, Belgium and Denmark presently recycle more than 80 percent of its construction and demolition waste.

In recent years many countries have considered the reutilization of construction and demolition waste as a new construction material as being one of the main objectives with respect to sustainable construction activities. From the mid 70’s many researchers have dedicated their work to describe the properties of these aggregates, the minimum requirement for their utilisation in concrete and the properties of concrete made with recycled aggregates. Many of the aforementioned countries have also started formulating their codes of practice/standards as guidelines for use of recycled aggregate for construction purpose.
1.2.2 Indian Perspective

Indian construction industry today is amongst the fifth largest in the world and at the current rate of growth, it is slated to be amongst the top two by the next century. It makes a significant contribution to the gross domestic product (GDP) growth and to national economy. The construction sector alone contributes around 8 percent of GDP and is the second largest economic activity after agriculture.

The contribution of construction to India’s GDP is likely to increase in the coming years with huge infrastructure projects taken up by the government in the Power and Highway sectors. As per the UN 1995 report it is believed that India will have more than 40 percent of its populace living in cities in the next 30 years. The Planning Commission of India has proposed an investment of around US$ 1 trillion in the Twelfth five-year plan (2012-2017), which is double of that in the Eleventh five-year plan. Growth in the current scenario is indispensable for a developing country like India.

Construction materials in general and aggregates in particular, are important components of infrastructure requirements. Projections for building requirement in the housing sector indicate a shortage of about 55000 million cum of aggregates and another 750 million cum is required to fulfill the target of the road sector. With the shortage as likely seen today, the future seems to be in dark for the construction sector. The projected requirements of natural raw materials are not only required to fulfill the demand for the upcoming projects, but also are the needs of the extensive repairs or replacements required for the existing infrastructure and structures built few decades back.

Fulfilling the demand of resources at present is one part but presently the construction industry is facing with the massive waste disposal problem. Estimated waste generated during construction is 40 to 60 kg/m^2 and during renovation another 40 to 50 kg/m^2 Technology
Information, Forecasting and Assessment Council TIFAC, 2002. The management of construction and demolition waste is a major concern due to increase in quantity of demolition rubble, continuing shortage of dumping sites, increase in cost of disposal and transportation and above all, the concern about environment degradation. In developing countries the amount of construction and demolition waste is constantly increasing owing to the rise in living standards, change in consumption pattern and normal growth of population. According to a survey conducted by Central Pollution Control Board, the estimated quantity of solid waste generated in India in 2007 was around 48 million tons per annum of which 25 percent was the waste from construction. The Energy and Resources Institute (TERI) has estimated that by 2047, waste generation in Indian cities will increase five-fold to touch 260 million tonne per year, implying that the current solid waste generation is over 50 million tonne per year (Kala and Kumar, 2013). They estimated the annual increase in the quantity of solid waste in Indian cities to be at the rate of 5 per cent per annum.

Presently in India this waste is disposed off in the landfill or used as an infill material. The poor management of solid waste has led to contamination of groundwater and surface water through leachate. Unscientific practices in processing and disposal in reclaimed areas or river banks compound the environmental hazards posed by solid waste. With landfill spaces decrease and environment being destroyed, this inert waste needs a better strategy to manage. Thus with huge demand seen in construction industry and strategies present to fulfill the demand, an integrated and holistic approach involving design and construction engineering is required which respects the construction and economic environment of the country.

Rapid strides are being made towards advancement of research in the field of construction material and technology. Recycle options have been tried to fulfill the growing demand which has led to the reuse of demolished waste in countries outside India. Research work on recycling of aggregates has also been carried out at Central Building Research Institute
(CBRI), Roorkee, and Central Road Research Institute (CRRI), New Delhi, but as per the study commissioned by (TIFAC), 70 percent of the construction industry is not aware of recycling techniques. Hence creating awareness as well as promoting the use of recycled product is the need of the day to achieve the necessary goal.

Thus it is seen that the problems in India are also alarming as in the west, considering the quantum of construction and demolishing waste generated. It is not far off when India may also have to seriously think of reusing demolished rubble and concrete for production of recycled construction material. Work on recycled concrete has been carried out at few places in India but waste and quality of raw material produced being site specific, tremendous inputs are necessary if India has to use the material in construction for producing concrete.

1.3 Aims and objective

The objective of this work is to analyse and propose technical guidelines on compressive strength, performance criteria and behaviour of concrete made with recycled aggregates. For recycled aggregates to be used in structural concrete, it is necessary to carry out an in depth study of their material properties and analyse how these properties in turn affect the quality of the second-generation concrete.

There is already very rich experience in some European countries, Japan and in the USA on quality control standards of recycled aggregates and guidance on using them in construction. Japan and other developed countries have even laid down specifications for use of recycled aggregate in concrete. Therefore it is necessary to prepare specifications for the use of this material in construction having regards to local conditions in India.

Recycled aggregates are obtained from the demolished waste crushed concrete. From a quality point of view, these aggregates are heterogeneous in composition being derived from different minerals and adhered mortar. The properties of these aggregates must be determined
if they are to be used in concrete, therefore an attempt is made to study the aggregate characteristics to be employed in concrete mixes.

Thus the objective of present work is

1) To characterize the recycled aggregates in terms of physical and chemical properties and also to study the properties of concrete made with recycled aggregates, to study the durability properties and lay standard guidelines for using recycled aggregate in concrete.

2) To analyze the structural behaviour of concrete made with different percentages of recycled coarse aggregates.

3) To analyze the option for the use of recycled aggregate in concrete in main stream construction rather than using it as an infill material.

4) To ameliorate the reservations if any, for the use of recycled aggregates in concretes and make the industry aware of the option available on recycling and reuse.

1.4 Hypothesis

**Hypothesis 1:** Research works signify that the concrete made using recycled aggregates does not provide the desired compressive strength. A reduction in compressive strength of around 15 to 25 percent is observed when recycled aggregates are used in making concrete. This work will assess such recycled aggregates and determine whether M25 grade concrete could be prepared. The work will also try to propose a mix design procedure to be adopted if recycled aggregates are to be used in producing concrete.

**Hypothesis 2:** Recycled aggregates are poor in their characteristics on account of the adhered mortar content which is porous. This attached adhered mortar is the cause of higher water absorption and lower specific gravity in case of recycled aggregates. It is observed from various research reports that it is on account of this adhered mortar that concrete made with recycled aggregates compromises on compressive strength. Thus this work would try to test
the material and find out possible alternatives to improve the quality of recycled aggregates so as to prevent its detrimental effect on concrete without imposing huge capital expenditure and be feasible to be applied on site for mass production.

**Hypothesis 3:** Any grade of concrete not only needs to provide the desired compressive strength but also to satisfy the criteria of performance during its serviceable life. Performance is generally understood by the ability of the material to resist strain and permeation of water and other aggressive agents. Since concrete prepared with recycled aggregate is porous on account of the adhered mortar content it would be essential to evaluate whether such concrete is also durable though it may provide the necessary compressive strength. Durability in the present context will be evaluated in terms of water permeability, chloride permeation, drying shrinkage, modulus of elasticity and creep strain in concrete prepared with recycled aggregates.

**1.5 Research Methodology**

The scope of work incorporated a rigorous experimental programme to establish the possible ways in which recycled aggregates could be used to provide a new concrete of M25 grade. The experimental program was conducted with a series of trial tests to ensure adequate strength gain with the new recycled material. The work included identification of ten different sites for the collection of construction and demolition waste (C&D) in Western Maharashtra. Since the C&D waste is available only on demolition of buildings or constructed structures, random method of sample selection was adopted for the study.

The C&D waste was processed for removal of impurities to obtain the recycled aggregates from ten different zones thus identified. Recycled aggregates therein were obtained by crushing of the old concrete procured from demolished sites. The material was first manually crushed and further crushed using a laboratory jaw crusher. The physical and mechanical
properties of this recycled aggregate material were studied owing to their site specific characteristics, as this influences the properties of concrete prepared. Finally the material was used in preparation of concrete and the behaviour of such concrete was tested for compressive strength and durability. The sequential steps in which the behaviour of recycled aggregate concrete has been studied in the present work is as shown in the Flow Chart 1.

Flow Chart 1: Research Flow Process
1.6 Structure of Thesis

The thesis is organized in nine chapters. A literature review of the properties of recycled aggregate, compressive strength and durability pertaining issues are given in Chapter 2. This chapter deals with various works undertaken by researchers and the methodology adopted by them to provide concrete with adequate compressive strength and durability using recycled aggregates. It also highlights the mechanism that is responsible for the deterioration of compressive strength in recycled aggregate concrete.

Chapter 3 consists of the properties of ingredients used in making recycled aggregate concrete. More emphasis has been given on recycled aggregate properties as this may be detrimental to the design of concrete. The chapter discusses the impact of all the ingredients used in making concrete and describes the procedure for testing of the same.

Chapter 4 provides insight into various methods that could be used to improve the quality of recycled aggregates by removal of the adhered mortar content. Since the quality of the material used is inferior on account of the adhered mortar traces left on the aggregates after crushing, state of the art test techniques and experimental procedures were used to study the possible ways in which the quality of the recycled aggregates could be improved. Various methods as available in literature were tried to evaluate the effective and economical method for improvement. Based on this, a method is proposed in this work to suit especially tropical Indian conditions that is found to be effective in removing a higher proportion of adhered mortar content and improved the performance of the aggregates in concrete.

Chapter 5 presents the comprehensive experimental work to achieve desired compressive strength with recycled aggregates. A compressive strength study consisted of testing recycled aggregates with adhered mortar and without adhered mortar until desired compressive strengths was achieved. Different mix design methods adopted for the design of normal
aggregate concrete were tried with recycled aggregate to achieve the desirable compressive strength. Compressive strength studies involved a test programme that consisted of casting of 186 cubes each of size 150×150×150mm for different combinations of size and proportion of recycled aggregates and normal aggregates.

In this work, 108 cubes were made of agglomerated sample from Pune Maharashtra (R_p) as an experimental trial to arrive at the desired strength and 60 cubes were from samples from other places in Western Maharashtra (R_1 to R_10) to validate the design process followed on the trial cubes. The remaining 18 were of control concrete (CC) using normal aggregates from Pune Maharashtra. Based on this, a mix design procedure is proposed in the present work to achieve M25 grade concrete using specific recycled aggregates.

The chapter also evaluates this concrete for standard deviation to understand the control mechanism that is necessary for working with recycled aggregates and explains on the failure mechanism as observed with recycled aggregate concrete.

Chapter 6 lays emphasis on the need of a model to predict compressive strength with recycled aggregate concrete. Recycled aggregates to be used in concrete require characterization, processing and proportioning to achieve adequate compressive strength which generally requires a rigorous experimentation programme. The process though is meticulous however is not assertive with the strength gain, thus it was felt necessary to make it predictable to understand the probability of the compressive strength attainment prior to making of concrete. The data thus obtained from the compressive strength studies was used to formulate a model that could be helpful to understand the behaviour and to make the process speedy which can be used with confidence for the predictions. The statistical model was developed by taking into account a set of diversified properties of recycled aggregates. Thus given the preliminary properties of recycled aggregates, the model can be employed to
estimate the possible compressive strength of this concrete without taking recourse to the laborious experimentation programme.

**Chapter 7** evaluates durability of such concrete which had satisfied the criteria of desired characteristic compressive strength to understand its long term behaviour. Various tests like drying shrinkage test, water permeability, rapid chloride permeability test, modulus of elasticity and creep studies were conducted on this concrete made with recycled aggregate to signify its performance.

**Chapter 8** shows the direct cost benefit that can be achieved using recycled aggregates in concrete in relation to normal aggregates thus specifying economic aspect for the construction industry. It also explains the indirect cost advantage that can be obtained by utilisation of recycled aggregate and emphasizes on the environmental and social benefits that can be achieved.

Finally, in **Chapter 9** the summary and main conclusions of the study are presented along with scope for future work.