

ENGINEERING PROPERTIES OF RECYCLED CONCRETE AND USED STEEL REINFORCEMENT BARS

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CERTIFICATION

I certify that this project was carried out under my supervision by OLAREWAJU, Akinola Johnson (CVE/98/1307) of the Department of Civil Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Akure, Ondo State, Nigeria.



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Date



DEDICATION

With love, I dedicate this piece of work to God, my wife and my entire family for their prayers and understanding.



ACKNOWLEDGEMENT

I wish to express my sincere gratitude to God who in His infinite mercy and grace gave me the courage and understanding during the course of this project. I also want to express my sincere gratitude to my supervisor Dr. C. Arum for his technical guidance, support and prayers and to my minor supervisor Dr. J.O. Babatola for technical and logistic supports. My gratitude goes to the immediate past Head of Civil Engineering Department - Prof. S.A. Ola for academic and administrative leadership of the Department, and to the present Head, Prof. J. O. Afolayan for reading through the entire text and making useful suggestions. Thanks are also due to the entire academic members of the Department in the persons of Prof. Ogedengbe, Dr. A.M. Oguntuase, Dr. A. O. Owolabi, Dr. C.S. Okoli, Engr. O. S. Aderinola, Engr. Aderinlewo, Engr. Mrs. Oluyemi Ayibiowu, Engr. O. O. Ojuri, as well as the technical and secretariat staff.

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ABSTRACT

This research was informed by the need to turn construction and demolition waste materials into resources so as to reduce demand for natural resources as well as reduce overall pollution and energy consumption while creating jobs at same time. The aim was therefore to determine the engineering properties of recycled aggregate concrete and recyclable steel with a view to ascertaining whether they can be used for normal concrete works. The research was carried out by means of laboratory experiments. Two groups of experiments were conducted. The first group was performed on three types of concrete produced using three different aggregates namely, original, washed recycled and unwashed recycled aggregates. For each type of these aggregate concrete types, experiments were conducted for grain size analysis, aggregate crushing value, workability, water absorption capacity, compressive strength, bending strength and modulus of elasticity. The second group of experiments pertained to reinforcing steel. For used steel of known and unknown origin, tests were conducted for tensile and yield strengths as well as percentage elongation and percentage reduction in area. From the results of this work, for washed recycled aggregate concrete, as the water-cement ratio increased by 0.05, water absorption capacity reduced by about 10% while unwashed recycled aggregate concrete has water absorption capacity ranging from 1.63% to 4.00%. The average densities of original aggregate concrete ranged from 2365kg/m^3 to 2449kg/m^3 , for washed recycled aggregate concrete, it ranged from 2375kg/m^3 to 2376kg/m^3 and for unwashed recycled aggregate concrete, it ranged from 2216kg/m^3 to 2262kg/m^3 to for the same water-cement ratio considered. The average compressive strength of original aggregate concrete ranged from 14.20 N/mm^2 to 43.30 N/mm^2 and that of washed recycled aggregate concrete ranged from 10.76 N/mm^2 to 31.41 N/mm^2 while that of unwashed recycled aggregate concrete ranged from 7.42 N/mm^2 to 19.70 N/mm^2 for the same water-cement ratio all considered at 28 days. The tensile and yield strengths of used steel of both known and unknown origin was 5% to 22% and 4% to 48% higher than the tensile and yield strength of the corresponding new steel of both known and unknown origin respectively while the percentage elongation and percentage reduction in area of used steel are 13% and 15% lower than the percentage elongation and percentage reduction in area of the corresponding new steel respectively, and finally

the modulus of elasticity for used steel of both known and unknown origin ranged from 202 to 208kN/mm². This work has established that the strength and ductility properties of used steel of known origin satisfy the minimum strength and ductility requirements as specified by the relevant codes, provided they are not used in structural members expected to take part in plastic action because of their reduced ductility. In addition, the research showed that not all ribbed steel bars in the market are indeed high yield since the tested ribbed steel bars of unknown origin gave strength and ductility values similar only to code requirements for mild steel. Lastly, this work has provided experimental evidence that provided the used steel of known origin is appropriately cleaned before reuse, the performance characteristics compare well with those of new steel of known origin, given the same types and equal cross sectional areas. Thus, if recycled aggregate is properly washed and used steel of known origin appropriately treated, they can be recycled for concrete works.

2.4	Density	9
2.5	Attached Mortar and Cement Paste	11
2.6	Water Absorption Capacity	11
2.7	Compressive Strength	12
2.8	Modulus of Elasticity	16
2.9	Bending Strength of Concrete	18
2.10	Strength and Ductility of Steel	22
2.10.1	Tensile strength	29
2.10.2	Yield strength or proof strength	29
2.10.3	Modulus of elasticity	29
2.10.4	Percentage elongation	29
2.10.5	Percentage reduction in area	30
2.10.6	Method of result evaluation	30
CHAPTER THREE		
RESEARCH METHODOLOGY		32
3.1	Introduction	32
3.2	Materials	32
3.2.1	Concrete rubbles	32
3.2.2	Used steel	32
3.3	Laboratory Test of Recycled Aggregate Concrete	34
3.3.1	Crushing of demolished concrete rubbles	34
3.3.2	Washing of recycled aggregate	34
3.3.3	Particle size distribution	35
3.3.4	Aggregate crushing value	35

3.3.5 Specific gravities of cement and aggregates	36
3.3.6 Workability tests	37
3.3.7 Water absorption capacity	38
3.3.8 Compressive strength	38
3.3.9 Bending strength	40
3.4 Laboratory Test of Used Steel	42
3.4.1 Preparation of used steel samples	42
3.4.2 Testing of used steel samples	42
CHAPTER FOUR	
RESULTS AND DISCUSSIONS	47
4.1 Results	47
4.2 Discussions	48
4.2.1 Aggregate crushing value	52
4.2.2 Specific gravities	52
4.2.3 Workability	55
4.2.4 Water absorption capacity	57
4.2.5 Densities	67
4.2.6 Compressive strength	68
4.2.7 Bending strength	71
4.2.8 Statistical analysis	71
4.2.9 Modulus of elasticity (E_c) of concrete	72
4.2.10 Modulus of elasticity (E_s) of steel	84
4.2.11 Used steel	89

4.2.12 Statistical analysis	96
4.2.13 Cost comparison of recycled and normal structural concrete	97
CHAPTER FIVE	
CONCLUSIONS AND RECOMMENDATIONS	98
5.1 Conclusions	98
5.2 Recommendations	100
REFERENCES	101
APPENDICES	109

LIST OF FIGURES

		PAGE
2.1	Curves indicating the limits specified in ASTM-C33 for fine aggregates and for four size members (grading size) of coarse aggregate.	7
2.2	Grading curves for 20mm maximum size aggregate.	8
2.3	Water absorption as a function of density of recycled aggregate concrete.	8
2.4	The relation between strength and water-cement ratio of concrete.	14
2.5	Typical relation between strength, water-cement ratio and compaction.	14
2.6	Typical relation between compressive strength and water-cement ratio for fully compacted dense aggregate concrete made with Portland cement to BS 12	15
2.7	Relation between flexural strength and compressive strength.	21
2.8	Typical relation between stress and strain for steel specimen.	24
2.9	Marking of reinforcing steel.	28



LIST OF TABLES

	PAGE
2.1 Observed Average Density of Original Aggregate Concrete.	9
2.2 Densities and Water Absorptions Capacity of Recycled Aggregate Concrete	10
2.3 Modulus of Elasticity of Concrete.	17
2.4 Gain in Bending Strength with Age of Typical Concrete.	20
2.5 Properties of Materials.	23
2.6 Typical Values of E and G.	25
2.7 Characteristics Values for Upper Yield Stress, Tensile Strength and Percentage Elongation after fracture.	25
2.8 Strength of Reinforcement	25
2.9 Marking of Country of Origin.	27
3.1 Aggregate Crushing Value Percentage Limit	36
4.1 Grain Size Analysis for Original and Recycled Aggregates.	48
4.2 Grain Size Analysis for Original Coarse Aggregate.	49
4.3 Grain Size Analysis for Original Fine Aggregate.	50
4.4 Grain Size Analysis for Recycled Coarse Aggregate.	50
4.5 Grain Size Analysis for Recycled Fine Aggregate.	51
4.6 Aggregate Crushing Value for Original Aggregate	51
4.7 Aggregate Crushing Value for Washed Recycled Aggregate	51
4.8 Aggregate Crushing Value for Washed Recycled Aggregate	51
4.9 Results of Specific Gravity Test.	51

4.10	Slump Test Result for Original Aggregate Concrete.	53
4.11	Slump Test Result for Unwashed Recycled Aggregate Concrete.	53
4.12	Slump Test Result for Washed Recycled Aggregate Concrete.	53
4.13	Result of Compacting Factor Test for Original Aggregate Concrete.	54
4.14	Result of Compacting Factor Test for Unwashed Recycled Aggregate Concrete.	54
4.15	Result of Compacting Factor Test for Washed Recycled Aggregate Concrete.	54
4.16	Water Absorption Capacity of Original Aggregate Concrete.	56
4.17	Water Absorption Capacity of Unwashed Recycled Aggregate Concrete.	56
4.18	Water Absorption Capacity of Washed Recycled Aggregate Concrete.	56
4.19	Densities and Compressive Strengths of Original Aggregate Concrete	58
4.20	Densities and Compressive Strengths of Unwashed Recycled Aggregate Concrete.	61
4.21	Densities and Compressive Strengths of Washed Recycled Aggregate Concrete.	64
4.22	Bending Strength of Original and Recycled Aggregate Concrete.	69
4.22-32	Stress-Strain Tables of Representatives 12mm and 16mm Diameters for Used Steel of Known Origin and Used Steel of Unknown Origin.	74
4.33	Tensile Strength	85
4.34	Yield Strength	86
4.35	Percentage Elongation	87
4.36	Percentage Reduction in Area	88
4.37	Statistical Analysis of Tensile Strength, Yield Strength, Percentage Elongation and Percentage Reduction in Area	92
4.38	Cost Analysis of Original and Recycled Aggregate Concrete	96
4.39	Cost Analysis of New Steel of both Known and Unknown Origin	96
4.40	Cost Analysis of Used Steel of both Known and Unknown Origin	97

LIST OF PLATES

	Page
Plate 1 Demolished Concrete Rubbles	33
Plate 2 Steel Specimen Types	33
Plate 3 Measurement of Slump	39
Plate 4 Compacting Factor Test	39
Plate 5 Bending Testing of Concrete Beams	41
Plate 6 Determination of Compressive Strength of the Two Halves of Failed Beam	41
Plate 7 Welding of Specimen	44
Plate 8 Testing Specimen with Extensometer	44
Plate 9 Dial Gauge Reading of Steel Specimen in Universal Testing Machine	45
Plate 10 Tensile Testing of Steel Specimen	45
Plate 11 Failed Steel Test Specimen	46

APPENDIXES

	PAGE
I Grading curve for original and recycled aggregate	109
II Water absorption capacity in percent against density of original aggregate concrete.	110
III Water absorption capacity in percent against density of washed recycled aggregate concrete.	111
IV Water absorption capacity in percent against density of unwashed recycled aggregate concrete.	112
V Compressive strength of original aggregate concrete against water-cement ratio.	113
VI Compressive strength of washed recycled aggregate concrete against water-cement ratio.	114
VII Compressive strength of unwashed recycled aggregate concrete against water-cement ratio.	115
VIII Stress-strain curve of 12mm diameter used steel of known origin.	116
IX Stress-strain curve of 11mm diameter used steel of unknown origin.	117
X Stress-strain curve of 16mm diameter used steel of known origin.	118
XI Stress-strain curve of 15mm diameter used steel of unknown origin.	119
XII Schematic diagram of bending strength test	120

CHAPTER ONE

INTRODUCTION

1.1 General

Recycled aggregates (which may be fine or coarse) are aggregates produced by the crushing of original concrete. Original aggregate concrete is the concrete from reinforced concrete structures, plain concrete structures or precast concrete units which can be used as raw material for production of recycled aggregates. Longman dictionary of Contemporary English defines recycling as the process of treating things such as paper, steel, or concrete through a special process so that they can be used again. Recycling comprises the recovery of recyclable waste, its processing into new materials or products, and the marketing of these new products. Building and construction waste material is a large part of building and construction waste derived from demolition, rehabilitation, and new construction following normal development, as well as from natural and technological disaster. Natural disasters such as earthquakes, tornado (hurricanes) etc. cause extensive damage to buildings. After the earthquake near Erzincan in Turkey on 13 March 1992, 6500 dwellings were destroyed or so severely damaged that they had to be demolished and rebuilt. The amount of building and construction waste after the earthquake had been assessed at between 500,000 and one million tons (Erik, 1994). Construction of roads and dualization of existing ones can greatly contribute to the bank of recyclable construction waste. For instance, the dualization of Lagos-Abeokuta road led to demolition of buildings in 2004 at Itori, Ewekoro and Ifo in Ogun State, Nigeria, while dualization of Abeokuta-Sagamu road in 2004 led to demolition of buildings.

1.2 Definitions

The following terminology and definitions shall be used in this investigation:

Original aggregates whether coarse or fine are the aggregates obtained directly from the quarry and riverbed while **recycled aggregates** whether coarse or fine are aggregates produced from crushing demolished concrete rubbles obtained from waste structural concrete.

Unwashed recycled aggregates whether coarse or fine are recycled aggregates that have old cement paste on them while **washed recycled aggregates** are recycled aggregates that have old cement paste on them removed by washing.

Original aggregate concrete is a mixture of original aggregates (coarse and fine), cement and water. On the other hand, **recycled aggregate concrete** is a mixture of recycled aggregates (coarse and fine), cement and water.

Unwashed recycled aggregate concrete is a mixture of unwashed recycled aggregates (coarse and fine), cement and water while **washed recycled aggregate concrete** is a mixture of washed recycled aggregates (coarse and fine), cement and water.

Steel of known origin: These are steel reinforcement bars found in Nigeria markets and which have identification marks that show their country of origin in accordance with ISO 6935 – 2 (1991) systems of marking.

Steel of unknown origin: These are steel reinforcement bars found in Nigeria markets and which do not have identification marks that show their countries of origin in accordance with ISO 6935 – 2 (1991) systems of marking.

New steel of known origin: These are steel of known origin that have not been subjected to stress other than stress associated with their production.

New steel of unknown origin: These are steel of unknown origin that have not been subjected to stress other than stress associated with their production.

Used steel of known origin are steel of known origin that were obtained from structural concrete that had been used and discarded.

Used steel of unknown origin: These are steel of unknown origin that were obtained from structural concrete that had been used and discarded.

In this investigation, in addition to tests on concrete, tests will also be carried out to determine the relevant properties of used steel of known origin and used steel of unknown origin while comparison was carried out between these properties and those of “new steel of known origin” and “new steel of unknown origin” as established in the works by Raji (2005) and Daodu (2005).

1.3 Justification for the Project

Waste should be treated as resources so that there will be reduction in demand for natural resources and the amount of waste requiring final disposal. Recycling reduces overall energy consumption and pollution and therefore has a vital role to play both in protecting the environment and in providing employment. The Recycling Market Development Zone programme (RMDZ) sponsored by the California Integrated Waste Management Board and the city created 1000 new jobs after 15 months of operation. According to Building Waste Generation and Recycling, there would be a need for approximately 20-25 billion tonnes of aggregates in the year 2000. This leads to the possibility of replacing up to 5 percent of the natural aggregate materials in a new concrete with recycled concrete. This need has increased in the present years.

1.4 Scope

This work involves extensive literature review and laboratory experiments on original, unwashed recycled and washed recycled aggregates. The experiments involved include particle size distribution, aggregate crushing value, workability tests, water absorption capacity, compressive strength and bending strength. As for steel, the laboratory experiments were limited to the determination of the tensile strength and yield strength as well as the determination of the ductility constants – percentage elongation and percentage reduction in area for the used steel of known origin and used steel of unknown origin. These properties for used steel will be compared with the properties of new steel of known origin and new steel of unknown of origin as established in earlier works (Raji, 2005; Daodu, 2005). Finally, statistical approach will be used for the evaluation of experimental results.

1.5 Aim and Objectives

This research is aimed at determining the engineering properties of recycled aggregate concrete and those of used steel reinforcement bars with a view to establishing the possibility of their use for normal concreting works while defining any inherent limitations. The specific objectives of the work are to determine:

- (1) the engineering properties (aggregate crushing value, density, water absorption capacity, compressive strength, modulus of elasticity and bending strength) of the recycled aggregate concrete, and
- (2) the engineering properties (tensile strength, yield strength, percentage elongation and percentage reduction in area) of used steel.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

According to Hansen (1992), once waste concrete has been crushed, sieved and if necessary decontaminated, it can find applications as (i) general bulk fill, (2) fill in drainage project, (3) sub-base or base material in road construction or (4) aggregate for new concrete if properly washed. It is on this note that recycled aggregates (fine and coarse) need to be thoroughly washed so as to have the same or comparable engineering properties as original aggregate.

2.2 Grain Size Analysis

Grading: This is the distribution of particles of granular material into various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of series of sieve openings or the percentages between certain ranges of sieve openings. Standard ASTM sieves for fine and coarse aggregates have a range of aperture sizes from 38 μ m to 125mm. According to Orchard (1976), aggregates should compose of inert matter, be clean, free from any adhering coating, dense, durable and sufficiently strong to enable the full strength of the cement matrix to be developed. The surface of the aggregate should be free from dirt, fine dust, silt, clay, or organic matter and should preferably be non-porous. According to Arum and Udo (2005), aggregates with 30% dust inclusion reduces concrete strength by 52% while dust content of 52% reduces the strength by 57%. Fine aggregate grading within the limits of ASTM C-33 is generally satisfactory for most concrete. Murdock and Brook (1979) defined fine aggregate as

those mainly passing a 5 mm BS410 test sieve and containing only so much coarse aggregate as is permitted for the various grading zones described in BS 882 (1973). Coarse aggregate within the limits of the four sizes of ASTM C-33 shown in Figure 2.1 is generally satisfactory for most concrete and grading curves for 20mm maximum size aggregate is shown in Figure 2.2. By their own definition, Murdock and Brook (1979) said that coarse aggregate are those mainly retained on a 5 mm BS 410 test sieve and containing only so much fines as is permitted for the various sizes described in BS 882 (1973). All - in - aggregate is an aggregate composed of a mixture of fine aggregate and coarse aggregate.

2.3 Specific Gravity

Specific gravity is defined as the ratio of unit weight of material to the unit weight of water (Bowles, 1982). Most original aggregates have specific gravities between 2.4 and 2.9. Two methods for determining specific gravities for coarse and fine aggregates are described in ASTM C-127 and C-128 respectively while details of laboratory procedure is contained in Bowles (1981). Neil and Ravindra (1996) said the specific gravity of most original aggregates falls within the range 2.5-3.0. Orchard (1976) explained further that the specific gravity of suitable original aggregates is normally above 2.5. Lydon (1979) affirmed that comparable data for original aggregates are in the range of 2.5 to 2.7. Ola (1983) gave the specific gravities of cement, lime, bitumen and soil to be 3.15, 2.20, 1.00 and 2.70 respectively.

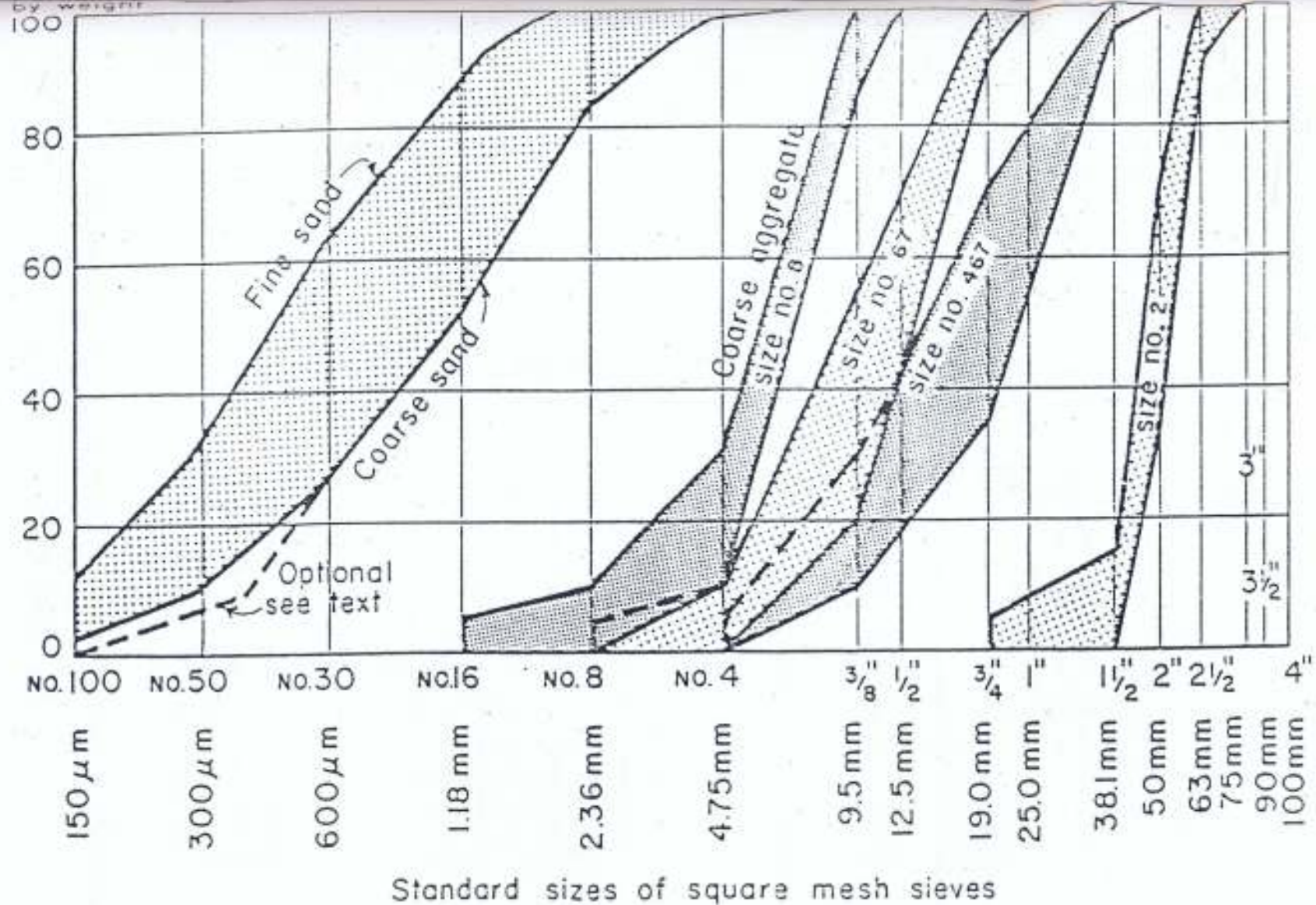


Figure 2.1 - Curves indicate the limits specified in ASTM C33 for the aggregate and for four size numbers (grading sizes) of coarse aggregate.

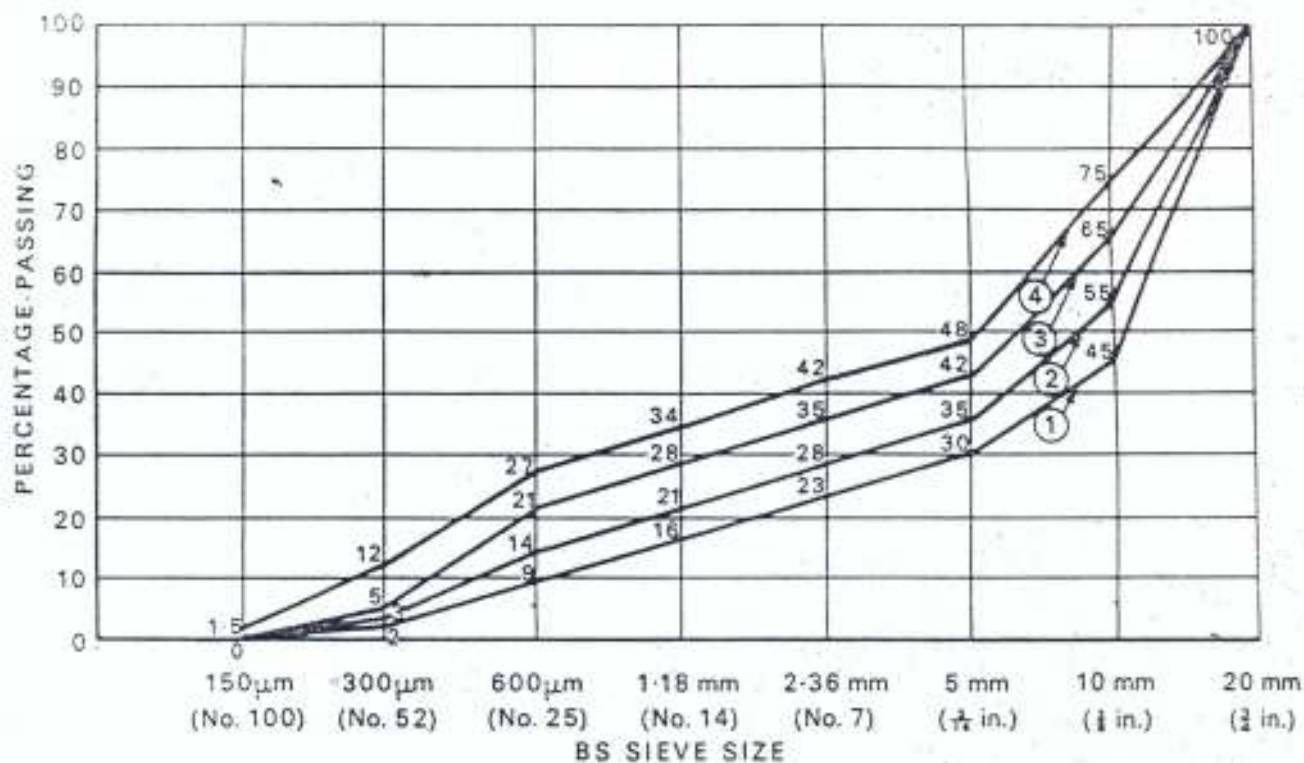


Figure 2.2 - Grading curves for 20mm (3/4 in.) maximum-size aggregate.

Source: Shacklock (1974)

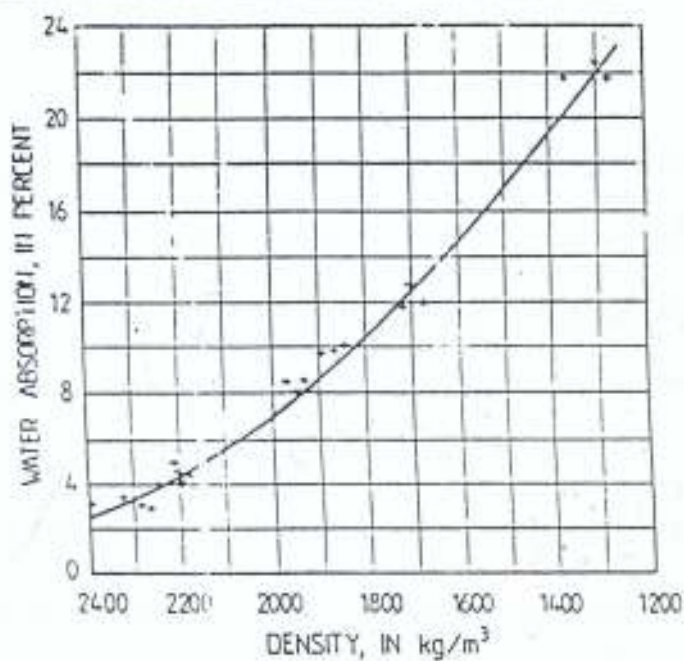


Figure 2.3 - Water absorption as a function of density of recycled aggregate concrete.

Source: Kreijger (1983)

2.4 Density

Density is the ratio of mass of material to its volume. Concrete that is normally used in pavements, buildings, and other structures has a density in the range of 2240 to 2400 kg/m³. The density of concrete varies, depending on the relative density of the aggregate, the amount of air that is entrapped or purposely entrained, and the water and cement contents as influenced by the maximum size aggregate. Values of the density of original aggregate concrete are given in Table 2.1.

Table 2.1 Observed Average Density of Original Aggregate Concrete

Maximum Size of Aggregate (mm)	Air Content percentage	Water (kg/m ³)	Cement (kg/m ³)	Density (kg/m ³)				
				Relative Density of Aggregate				
				2.55	2.60	2.65	2.70	2.75
19	6.0	168	336	2294	2227	2259	2291	2323
38	4.5	145	291	2259	2291	2339	2371	2403
76	3.5	121	242	2347	2355	2387	2435	2467
152	3.0	97	167	2355	2387	2435	2467	2515

Source: Powers et al (1966)

Shacklock (1974) said the density of original aggregate concrete is in the range of 2300 kg/m³ to 2650 kg/m³. Also Lyndon and Kenneth (1979) submitted that in general, dense, well-compacted concrete as described in the appropriate code of practice provides an excellent protective environment in the long-term for steel reinforcement embedded within it. Accordingly, John and Richard (1979) in their investigation into the structural defects and collapse of Ferry Comprehensive School, Birkenhead, in 1976 discovered that it was due to lack of cover to reinforcement due to poor compaction of in-situ



concrete which later resulted to corrosion of embedded reinforcement. Hansen and Narud (1983) found densities of coarse recycled aggregates concrete ranging from 2340 kg/m³ (for 4-8 mm material) to 2490 kg/m³ (for 16-32 mm material) while the corresponding densities of original coarse aggregates concrete ranged from 2500 to 2610 kg/m³. In addition, report of B.C.S.J (1978) indicated that the densities of recycled aggregate concrete varied between 2120 kg/m³ and 2430 kg/m³. Similar results were found by Karindrarajah and Tam (1985). And finally, Hansen (1992) concluded that the density of recycled aggregate concrete is somewhat lower than the density of original aggregate concrete due to a relatively low density of old mortar which is attached to original aggregate particles. Values of densities of recycled aggregate concrete as adopted from Hansen and Narud (1983) is presented in Table 2.2

Table 2.2 Densities and Water Absorption Capacity of Recycled Aggregates Concrete.

Water/cement	Size of Aggregate in mm	Density in kg/m ³	Water Absorption in percent
0.40	4-8	2036	17.0
	8-16	2060	17.0
	16-32	2140	15.6
0.70	4-8	2041	17.0
	8-16	2060	16.2
	16-32	2091	15.8
1.20	4-8	2070	16.5
	8-16	2068	16.6
	16-32	2081	16.5

Source: Hansen and Narud (1983)

2.5 Attached Mortar and Cement Paste

Hansen (1992) admitted that when old concrete is crushed, a certain amount of mortar from the original concrete remains attached to stored particles in the recycled aggregate. Recycled aggregate has to be thoroughly washed.

2.6 Water Absorption Capacity

Durability of concrete according to Neil and Ravindra (1996) is resistance to deterioration processes that may occur as a result of interaction with its external environment, or between the constituent materials or their reaction with contaminants present. According to the same source, absorption which is also a measure of durability is the process by which concrete takes in a liquid e.g. water or aqueous solution, by capillary attraction and the rate at which water enters is termed absorptivity (or sorptivity) which depends on the size and interconnection of the capillary pores in concrete, and the moisture gradient existing from the surface. Furthermore, permeability is the flow property of concrete which quantitatively characterizes the ease by which a fluid passes through it, under the action of a pressure differential. This property depends on the pressure gradient and on the size and interconnection of the capillary pores in concrete. Assessment of the resistance of concrete to potential damage can be made through measurement of permeation properties which define the ease with which agents can move into or out of concrete (Dlir et al., 1987). According to Neville (1981), the most marked difference in physical properties of recycled aggregate concrete compared with original aggregate concrete is higher absorption rate. In addition to the foregoing, Kreijger (1983) found a parabolic relation between water absorption and density of

recycled aggregate concrete as shown in Figure 2.3. Hansen and Narud (1983) in their work found water absorptions of coarse recycled aggregate concrete to range from 8.7% for 4-8 mm material to 3.7% for 16-32 mm material.

2.7. Compressive Strength

The compressive strength of concrete is empirically a function of the following: water/cement ratio, compaction, cement type, aggregate type, aggregate/cement ratio, specimen type, and geometry, testing procedure, age and curing maturity. It is also necessary to determine the proportions of cement, fine and coarse aggregate, and water which will attain a specified strength at 28 days (or other specified age) which meets the requirement of the designer of the structure. Furthermore, durability is related to compressive strength, the greater the strength, the more durable the concrete (Murdock and Brook, 1979). According to Lydon (1979) the strength may be classified into compressive, tensile and bond strength. The last two strengths are roughly related to compressive strength, which makes the latter as a measure of general strength of concrete. When concrete is fully compacted, its strength is taken to be inversely proportional to water/cement ratio according to Neville (1981), and as a result of this, water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. Therefore the water/cement ratio and the degree of compaction both affect the volume of voids in concrete. The hydration reaction consumes a specific amount of water. The extra water is needed to give concrete sufficient workability. Figures 2.4 and 2.5 adopted from Neville (1981) and Lydon (1979) respectively shows fully compacted and insufficient compacted concrete, while Figure 2.6 adopted from Shacklock (1974) shows the relation between

water/cement ratio and compressive strength for fully compacted dense aggregate concrete made with Portland cement to BS 12. To further bring the above to focus, Shacklock (1974) pointed out that the data apply to fully compacted original aggregate concrete made with natural dense aggregate and cured at a temperature of about 15°C, sulphate-resisting Portland cement and Portland blast-furnace cement should be treated as ordinary Portland cement, and experience has shown that somewhat higher strengths may be expected with concretes of low and very low workability and, conversely, that lower strength may be expected with concretes of very high workability. On the other hand, the compressive strength of recycled aggregate concrete depends on the strength of the original aggregate concrete, and is largely controlled by a combination of the water-cement ratio of the original aggregate concrete and the water-cement ratio of the recycled aggregate concrete when other factors are essentially identical (Hansen and Narud, 1983). If the water-cement ratio of the original aggregate concrete is the same as or lower than that of the recycled aggregate concrete, then the strength of the recycled aggregate concrete can be as good as or higher than the strength of the original aggregate concrete. The workability of original aggregate concrete mix is higher than that of recycled aggregate concrete. Furthermore, B.C.S.J. (1978) in Japan arrived at the conclusion on the basis of experimental results which showed compressive strength of recycled aggregate concrete to be between 14% and 32% lower than that of original concrete. Finally, Nixon (1978) in his work concluded that the compressive strength of recycled aggregate concrete is somewhat lower (in some cases up to 20%, but usually less) compared with the strength of control mixes of original aggregate concrete.

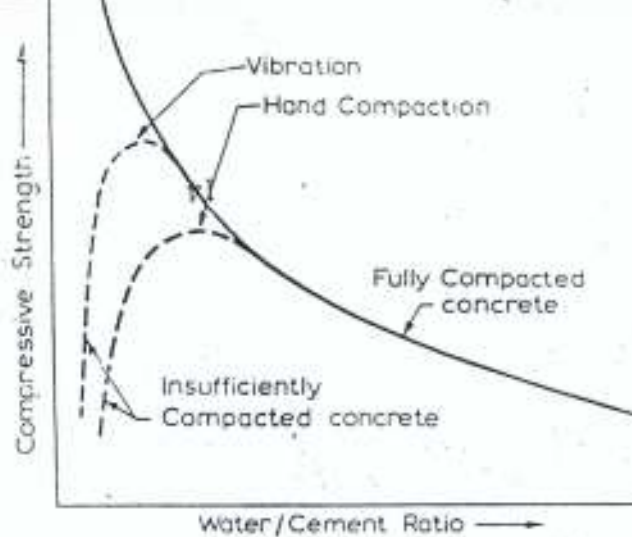


Figure 2.4 - The relation between strength and water/cement ratio of concrete.

Source: Neville (1981)

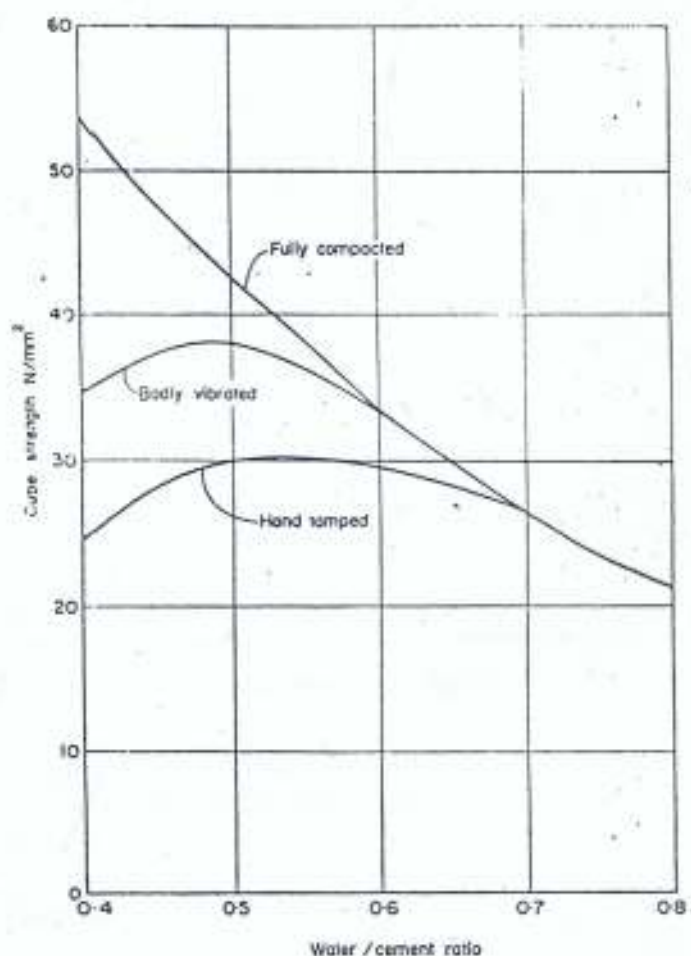


Figure 2.5 - Typical relation between strength, water/cement ratio and compaction.

Source: Lydon (1979)

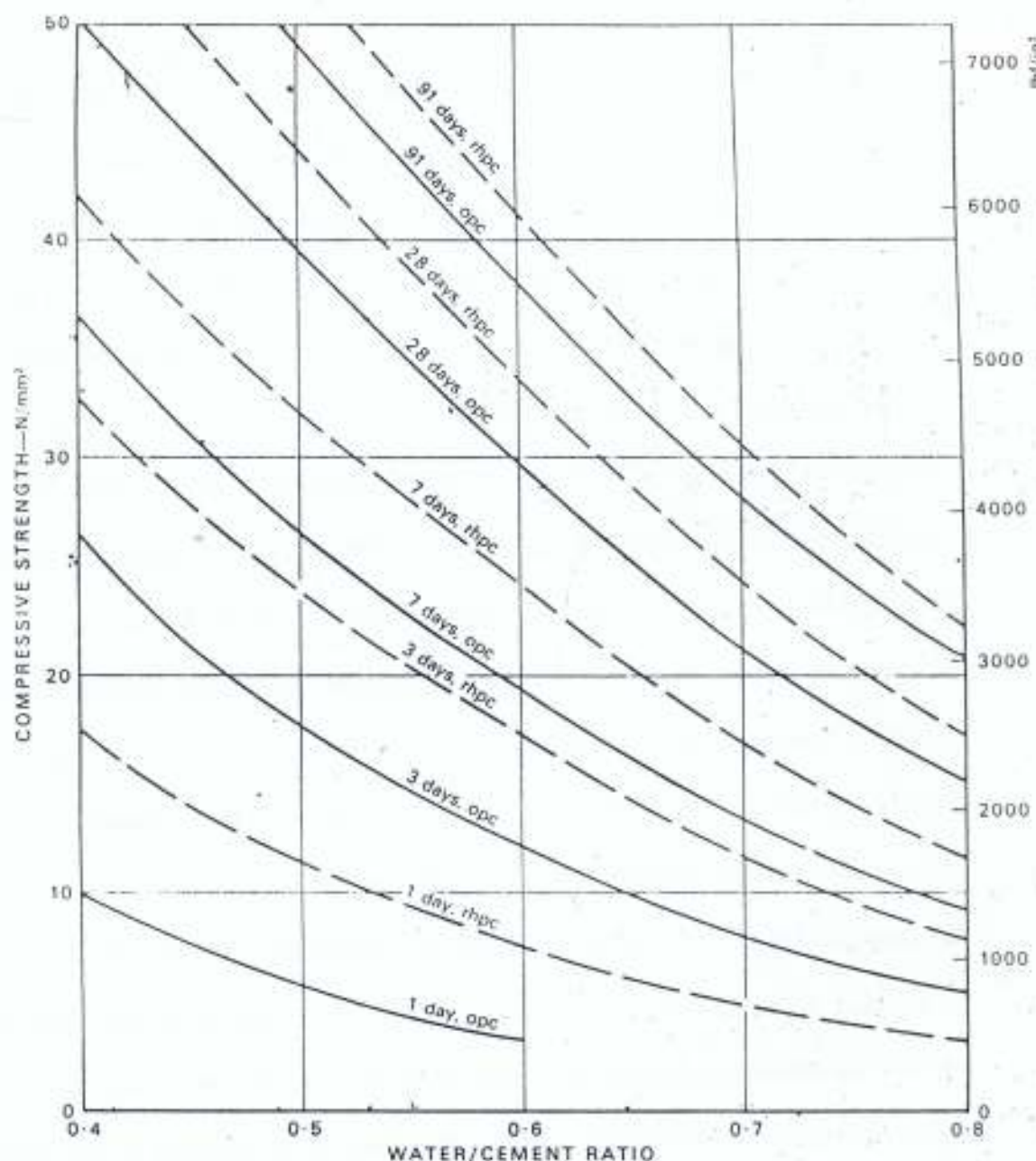


Figure 2.6 - Typical relation between compressive strength and water/cement ratio for fully compacted dense aggregate concrete made with Portland cement to BS 12.

Source: Shacklock (1974)

2.8 Modulus of Elasticity of Concrete, E_c

Modulus of elasticity is defined as the ratio of stress to strain and is given by,

$$E = \frac{\text{Stress}}{\text{Strain}} \quad (2.1)$$

Basically there are two types of moduli, static and dynamic. Static modulus is measured for a particular concrete by means of a static test in which a cylinder is loaded to just above one-third of the corresponding control cube stress and then cycled back to zero stress. This removes the effect of stress redistributions in the concrete under load. Load is then reapplied and the behavior will then be almost linear; the average slope of the line up to the specified stress is taken as the value for static modulus. The test is described in detail in BS 1881 (1970). The standard test is based on determining the resonant frequency of a laboratory prism specimen and details are also described in BS 1881 (1970). It is also possible to obtain a good estimate of dynamic modulus from ultrasonic measuring techniques, which may sometimes be used on site to assess the concrete in an actual structure. The standard test for dynamic modulus is on an unstressed specimen (Mosley and Bungey, 1995). The same source explained further that a general relationship is considered to exist between the modulus of elasticity and the compressive strength. Thus, the magnitude of modulus of elasticity is required when investigating the deflection and cracking of structure. Modulus of elasticity is important in calculating loss of stress in prestressed concrete owing to elastic movement, recoverable movement under load, and it depends on factors such as: age of concrete, water/cement ratio, aggregate/cement ratio, type of aggregate and method of test (Lydon, 1979). Table 2.3 as adopted from Shacklock (1974) gives the modulus of elasticity for different compressive strengths. This value is in agreement with values given by Neville (1981), Lydon (1972)

and Mosley and Burgey (1995). When it is required to estimate the static modulus of concrete from the dynamic modulus, the following equation given by Shacklock (1974) will give an estimate accurate to about 4 kN/mm^2 , which is in agreement with Mosley and Burgey (1995).

$$E_c = 1.25 E_d - 19 \quad (2.2)$$

Where E_c = Static modulus in kN/mm^2

E_d = Dynamic modulus in kN/mm^2

Table 2.3 Modulus of Elasticity of Concrete, E_c

Compressive strength at 28 days – N/mm^2	Static Modulus (kN/mm^2)		Dynamic Modulus (kN/mm^2)	
	Typical range	Mean value	Typical range	Mean value
20	21-29	25	31-39	35
25	22-30	26	32-40	36
30	23-33	28	33-43	38
40	26-36	31	35-45	40
50	28-40	34	36-48	42
60	30-42	36	38-50	44

Source: Shacklock (1974)

In comparison, due to the large amount of old mortar attached to original aggregate particles in recycled aggregates, the modulus of elasticity of recycled aggregate concretes is always lower than that of corresponding control concretes made with original aggregates. In agreement with this, Frondiston-Yannas (1977) in his work found that the modulus of elasticity for recycled aggregate concretes could be up to 33% lower than the modulus of elasticity of corresponding control concretes made with original aggregates. Furthermore, Ravindrarajah et al. (1987) concluded that modulus of elasticity of recycled

aggregate concrete is lower than that of original aggregate concrete for as much as about 25% to 35% and the difference increases with strength. In evaluation, a minimum value for the modulus of elasticity of recycled aggregate concrete E_c to be used in the design of structures made from such concrete can be calculated from,

$$E_c = 2.1 \times 10^5 \times \left[\frac{\alpha}{2.3} \right]^{1.5} \times \sqrt{f_c / 200} \quad (2.3)$$

When the compressive strength, f_c and the density, α , of the recycled aggregate concrete are known (Hansen, 1992).

2.9 Bending Strength of Concrete

The flexural strength of concrete section is reached when the strain in the extreme compression fibre of the concrete is approximately 0.003. Park and Panley (1975) highlighted four basic assumptions made when desiring a general theory for the flexural strength of reinforced concrete sections.

- (1) Plane sections before bending remain plane after bending.
- (2) The stress-strain curve for the steel is known.
- (3) The tensile strength of the concrete may be neglected.
- (4) The stress-strain curve for concrete, defining the magnitude and distribution of compression stress is known.

According to Orchard (1976), the flexural strength increases with the weight of the concrete but becomes relatively less in comparison with the compressive strength as the compressive strength increases. The flexural strength of lightweight concrete is far

greater in proportion to its compressive strength than for normal weight concrete. The same author estimated the modulus of rupture or extreme fibre stress in tension M , if w is

$$m = \frac{wl}{bd^2} \quad (2.4)$$

the load applied by the testing machine, L , the effective span, b , the width of beam at point of failure, d , the depth of beam at point of failure and, l , the distance from the failure point to the nearest support measured along the center line of the tension face, when failure takes place within the middle third of the span,

When failure takes place outside the middle third of the span,

$$m = \frac{3wl}{bd^2} \quad (2.5)$$

These formulae are derived from ordinary beam relation of

$$\frac{\text{Bending moment}}{\text{Moment of Inertia of section}} = \frac{\text{extreme fibre stress}}{\text{half effective depth}} \quad (2.6)$$

Mourdock and Brook (1979) explained that test specimens in the form of beams 150 x 150 x 750 mm long or 100 x 100 x 500 mm long are used to measure the modulus of rupture quickly on the site. The two halves of the specimen may then be crushed so that besides the flexural strength the compressive strength can be approximately determined on the same sample in accordance to BS 1881 (1970). Values of the modulus of rupture are utilized in some methods of design of unreinforced concrete roads and runways in which reliance is placed on the flexural strength of the concrete to distribute concentrated loads over a wide area. Lydon (1979) in his work relates modulus of rupture to compressive strength in the form

$$F_b = a\mu^b \quad (2.7)$$

Where F_b is the modulus of rupture (N/mm^2), μ is the compressive strength (N/mm^2) and a , b are constants whose values depends upon the size of beam, the method of test and the

type of aggregate. Figure 2.7 adopted from Shacklock (1974) gives the flexural strength of concrete. Table 2.4 gives data, based on Road Research Technical Paper No. 67 for concretes of four different levels in terms of their 28-day strengths and for two types of aggregate.

Table 2.4 Gain in Flexural Strength with Age of Typical Concrete

Aggregate Type	28-day Strength (N/mm ²)	Percent of 28-day strength at			
		7 days	28 days	3 months	1 year
Gravel and sand	4.5	89	100	114	128
	4.0	89	100	114	130
	3.5	86	100	116	134
	3.0	81	100	117	131
Crushed rock and sand	6.0	83	100	112	110
	5.0	81	100	118	124
	4.5	77	100	117	127
	4.0	74	100	120	132

Source: Road Research Technical Paper, No. 67.

- * The flexural strength of recycled aggregate concrete according to B.C.S.J (1978) is somewhere between 1/5 or 1/8 of its compressive strength, similar to what is the case for original aggregate concrete, but no experimental data are presented.

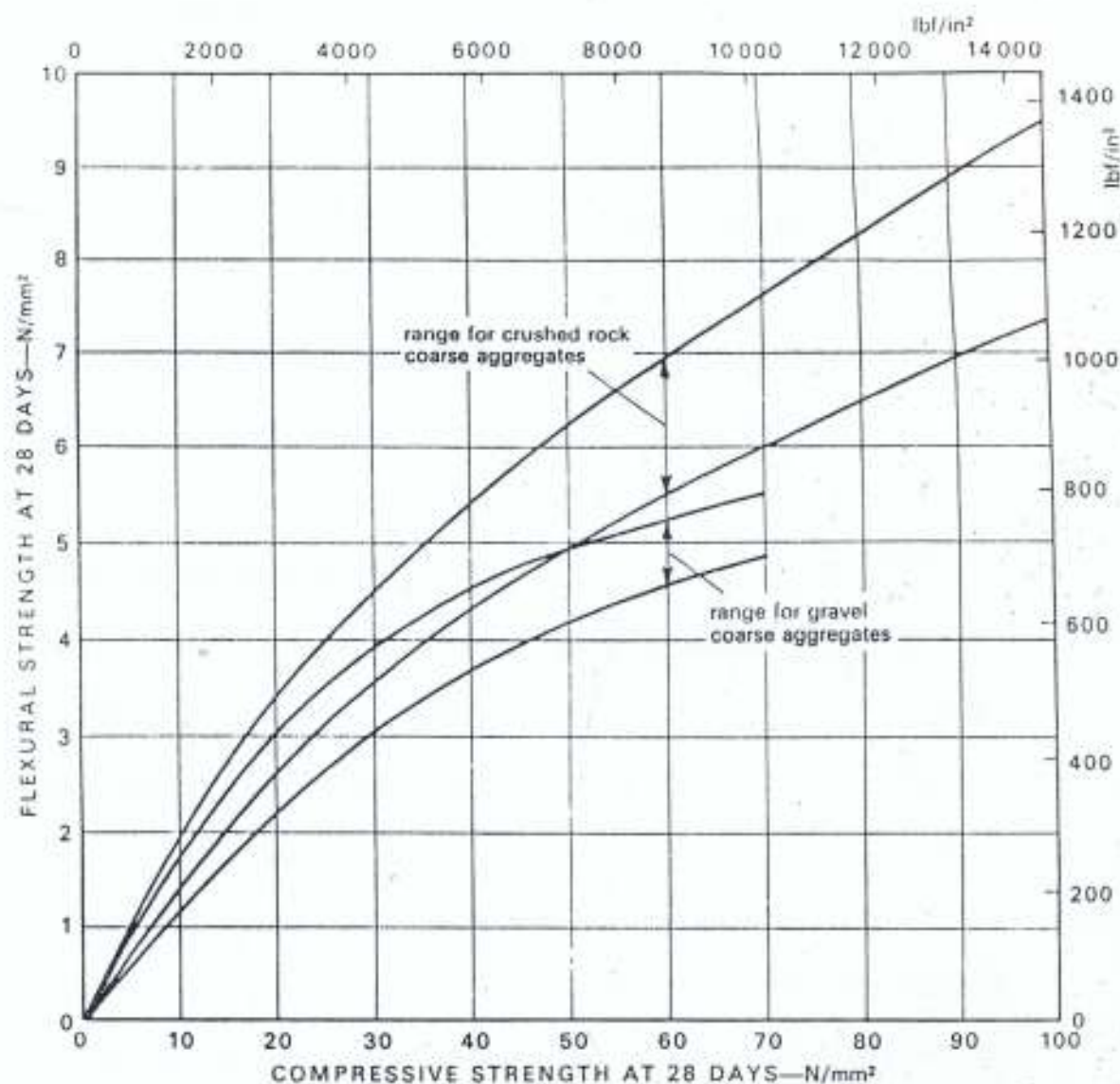


Figure 2.7 - Relation between flexural and compressive strength.

Source: Shacklock (1974)

2.10 Strength and Ductility of Steel

According to Fenner (1986), the solution of a static elastic problem, or indeed of any static solid mechanics problem, must satisfy the following requirements,

- (i) equilibrium of forces and moments at all points within the bodies concerned.
- (ii) compatibility of strains throughout, ensuring continuity of material.
- (iii) constitutive equations linking stresses and strains, which reflect the physical properties of the materials concerned.
- (iv) boundary conditions for the particular problem.

For a linearly elastic material, the general form of constitutive equation is

$$\text{Stress} = (\text{a constant}) \times \text{strain} \quad (2.8)$$

The constant of proportionality has the dimension of stress. Thus under uniaxial load,

$$\text{Stress} = E \times \text{strain} \quad (2.9)$$

Where E is Young's modulus or the modulus of elasticity of the material.

The stress-strain relations hold for a wide range of stresses in most practical materials.

They become invalid when the interatomic bonds in the materials break down, this process generally being called **Yielding**. This yielding can be demonstrated by tensile test, where known stress system,

$$\sigma_x \neq 0, \sigma_y = \sigma_z = \tau_{xy} = \tau_{yz} = \tau_{zx} = 0 \quad (2.10)$$

called **uniaxial stress**, σ is induced in a specimen and the corresponding strain, ϵ is measured. A typical plot of σ_x (stress) versus ϵ_x (strain) for a mild steel and high yield steel specimen takes the form shown in Figures 2.8 a, b adopted from Gravesmith (1985).

Values of Modulus of elasticity E , Poisson's ratio ν and Temperature coefficient of

expansion α (per deg C^0) for a variety of practical materials adopted from Gravessmith (1985) are given in Table 2.5.

Table 2.5 Properties of Materials

Material	Density (kg/m ³)	E GN/m ²	ν	α (per deg C ⁰)	Limit of Proportionality (MN/m ²)	Ultimate stress (MN/m ²)	Uniform Elongation
Mild steel	7840	200	0.31	1.25×10^{-5}	280	370	0.30
High-Strength Steel	7840	200	0.31	1.25×10^{-5}	770	1550	0.10
Medium Strength aluminium alloy	2800	70	0.30	2.3×10^{-5}	230	430	0.10
Timber	576	7		0.6×10^{-5}	43	52	-

Source: Gravessmith (1985)

Benham and Crawford (1991) in their work presented typical values of Modulus of elasticity E and Modulus of rigidity G for a few materials as shown in Table 2.6. Furthermore, B.S 5950 specifies the modulus of elasticity of steel, E to be 205 GN/m² (205000 N/mm²).

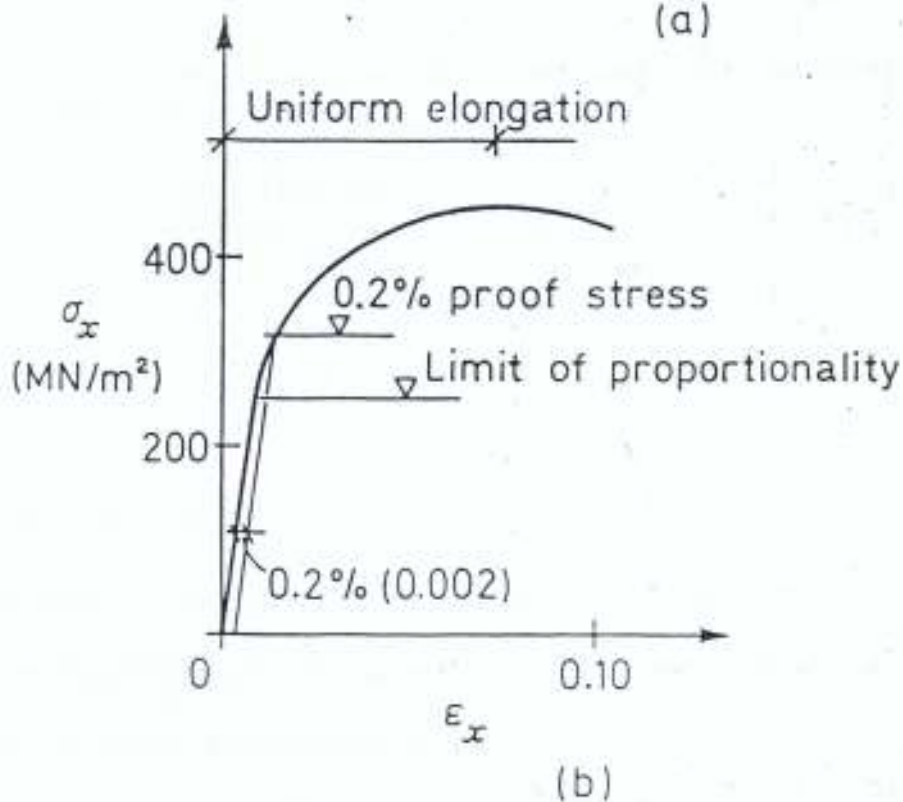
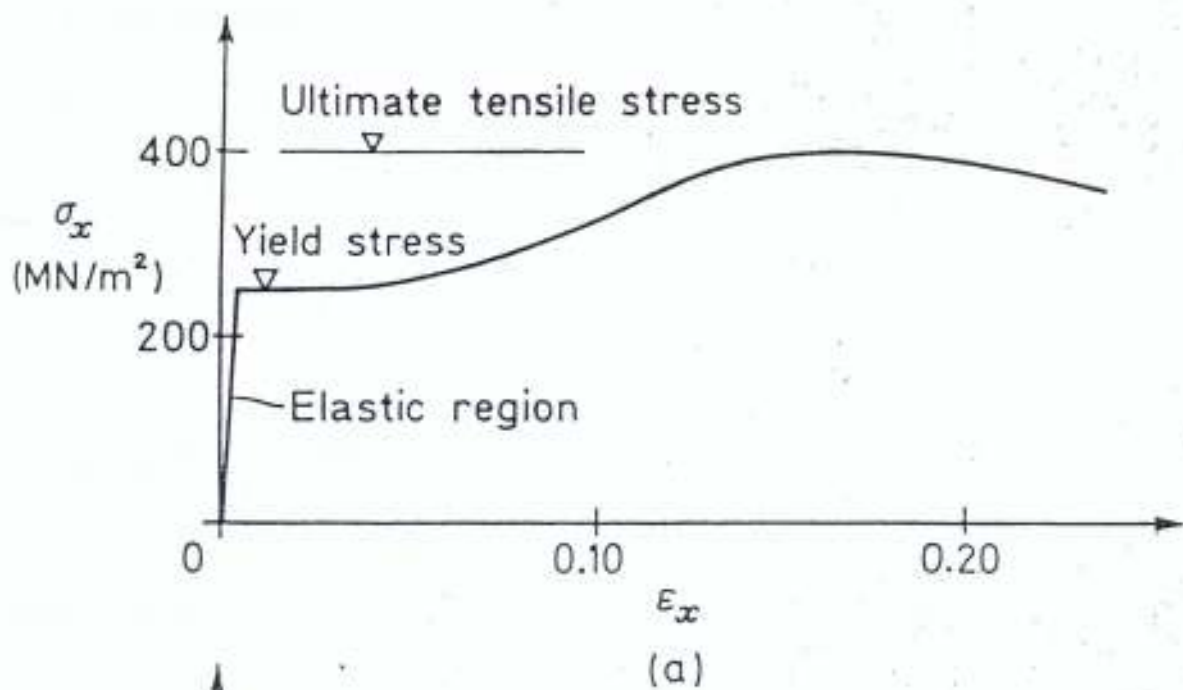


Figure 2.8 - Typical relation between stress and strain for steel specimen.

Source: Gravessmith (1985)

Table 2.6 Typical Values Of E And G.

Materials	E (GN/m ²)	G (GN/m ²)
Steels	190-207	77 – 83
Copper	110-120	37 – 46
Aluminium	69-70	24 – 28
Glass	50-80	20 – 35

Source: Benham and Grawford (1991)

The required tensile properties for various steel grades are given in Table 2.7 adopted from ISO 6935-2 (1991).

Table 2.7 Characteristics values for upper yield stress, tensile strength and percentage elongation after fracture.

Steel grade	Upper Yield Stress (N/mm ²)	Tensile Strength (N/mm ²)	Elongation (%)
RB 300	300	330	16
RB 400 RB 400 w	400	440	14
RB 500 RB 500 w	500	550	14

Source: ISO-6935-2 (1991)

The characteristic strength of reinforcement specified according to BS 4449 and BS 8110 is shown in Table 2.8, which is also presented by Mosley and Bungey (1995).

Table 2.8 Strength of Reinforcement

Designation	Specified characteristic strength, f_y (N/mm ²)
Hot rolled mild steel	250
High yield Steel (hot rolled or cold worked)	460

Source: BS 8110 Part 1 (1997)

According to Chidolue (2005), British Steel design practice utilizes only three grades of steel (Grades 43, 50, and 55) with yield stresses of 250 N/mm^2 , 350 N/mm^2 and 430 N/mm^2 respectively. BS 4449, which applied equally to hot rolled cold worked steel bars, specified the required property for **plain round steel** bars in **grade 250** and **deformed high yield steel** bars in **grade 460** for use as reinforcement. The **grade number** is the **characteristic strength** of the steel in N/mm^2 and is the **yield** or **0.2 percent proof strength**, below which not more than 5 percent of the test results for the material supplied and tested, shall fall. Williams et al., (1985) allowed for a safety margin against failure by introducing factor of safety so that

$$\text{Design strength} = \frac{\text{Ultimate (or Yield strength)}}{\text{Factor of safety}} \quad (2.11)$$

The results of the works by Raji (2005) and Daodu (2005) showed in great details the strength and ductility characteristics of new high yield reinforcement bars from different countries of the world (including those locally produced in Nigeria) and used in our construction sector. According to ISO 6935 – 2 (1991), high yield ribbed bars are identified in two ways:

- (1) System according to EURONORMS 80 – 85, and
- (2) System according to ASTM A 615 M – 88.

The markings of the steel for these two systems are shown in Figure 2.9. According to the EURONORM 80 – 85 system, two steel grades RB400 and RB 500 are differentiated in the following ways; steel grade RB400 is indicated by means of two opposed rows of parallel oblique ribs. The oblique ribs are at different intervals on each half of the circumference as shown in Figure 2.9A (1). Steel grade RB 500 is indicated by means of two rows of oblique ribs, one row consisting of parallel ribs and the other ribs with

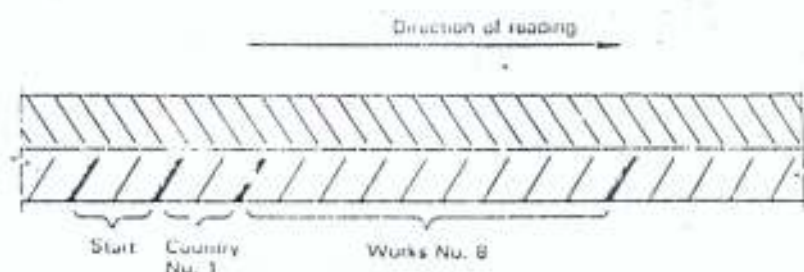
alternating angles of inclination towards the axis of the bar as shown in Figure 2.9A (11). Marks are made on steel of different grade to indicate their country of manufacture as shown in Table 2.9 adopted from ISO 6935 – 2 (1991).

Table 2.9 Marking of Country of Origin

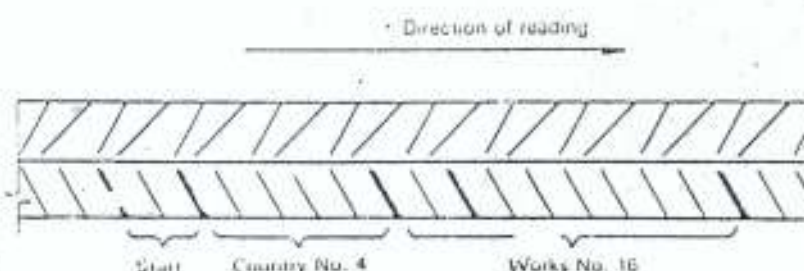
Country	Number of normal oblique ribs between two thickened oblique ribs
Germany	1
Belgium, Netherlands, Luxemburg	2
France	3
Italy	4
UK, Ireland	5
Denmark, Sweden, Norway, Finland	6
Spain, Portugal	7
Greece, Turkey, Czechoslovakia	8

Source: ISO 6935-2 (1991)

Notwithstanding the grade however, the steel is marked for easy identification of its country of origin. Table 2.10 shows how the country of origin can be identified by the number of normal oblique ribs between two thickened oblique ribs on the steel bars. The system according to ASTM A 615 M – 88 is well illustrated in Figure 2.9 B. A close study of the works by Raji (2005) and Daodu (2005) referred to above showed that the steel referred to as imported are those marked in accordance with either the EURONORM 80 – 85 or the ASTM A 615 M – 88 systems. In the said works, all reinforcement bars without markings to clearly identify their countries of origin were referred to as locally produced steel while those with clear identification of country of origin were referred to as imported steel.

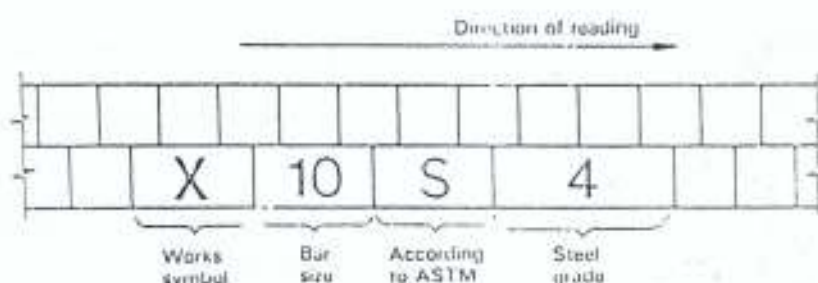


(I) Marking of reinforcing steel RB 400



(II) Marking of reinforcing steel RB 500

(A) According to EURONORM 80-85



(B) Marking of reinforcing steel according to ASTM A 615 M - 88

Figure 2.9 - Marking of reinforcing steel.

In the present research, the steel referred to as imported in the works of Raji (2005) and Daodu (2005), will be called “**steel of known origin**” while those referred to as locally produced steel in the said works, will be called “**steel of unknown origin**”.

2.10.1 Tensile strength is given by

$$\text{Tensile strength} = \frac{\text{Maximum load applied}}{\text{Original cross-sectional area}} \quad (2.12)$$

The unit is N/mm^2 or megapascals (Mpa). Numerically these values are equal.

2.10.2 Yield point or yield strength is given by

$$\text{Yield strength} = \frac{\text{Yield point load}}{\text{Original cross-sectional area}} \quad (2.13)$$

Proof Strength or offset strength is given by

$$0.2\% \text{ Proof Strength} = \frac{0.2\% \text{ Proof force}}{\text{original cross-sectional area}} \quad (2.14)$$

2.10.3 Modulus of elasticity (Young’s modulus) E, is calculated from the slope of the elastic portion of the force-extension curve. E is given by

$$\text{Slope} \times \frac{\text{gauge length}}{\text{Cross-sectional area}} \quad (2.15)$$

2.10.4 Percentage elongation. It is a measure of ductility of material. For an elongation value to have validity the fracture must occur in the central section of the gauge length and the gauge length must be specified.

$$\% \text{ Elongation} = \frac{\text{Extension}}{\text{Original gauge length}} \quad (2.16)$$

The elongation value for any particular material will be higher if measured over a short gauge length than if measured over a long gauge length.

2.10.5 Percentage reduction of area. This is also a measure of ductility and is often quoted instead of percentage elongation value.

$$\% \text{ Reduction of area} = \frac{[A_0 - A]}{[A_0]} \times 100 \quad (2.17)$$

Where A_0 is the original cross-sectional area and A , is the cross-sections area at the point of fracture (Neil and Ravindra, 1996) and (Chapman, 1975). ISO 6935-2 (1991) specified that test pieces shall be taken from each test unit as fifteen (15) test pieces from various bars for testing.

2.10.6 Method of result evaluation

According to the provisions of ISO 6935-2 (1991) for properties which are specified as characteristic values, the following shall be determined.

- (a) all individual values, x of the 15 test pieces ($n = 15$).
- (b) the mean value, m_{15} (for $n = 15$).
- (c) the standard deviation, s_{15} (for $n = 15$).

The test unit corresponds to the requirements if the condition stated below is fulfilled for all properties.

$$m_{15} - 2.33 \times s_{15} \geq f_k \quad (2.18)$$

Where f_k is the required characteristic values,

2.33 is the value for the acceptability index,

k , for $n = 15$ for a failure rate of 5% ($P = 0.95$) and a probability of 90% ($1 - \alpha = 0.90$)

$$\text{Average, } m = \frac{\sum x}{n} \quad (2.19)$$

$$\text{Standard Deviation } s, = \sqrt{\sum (x - m)^2 / (n-1)} \quad (2.20)$$

where s is the standard deviation

n is the number of values in the set

x is any value in the set number

m is the average of the set number (Murdock and Brook ,1979)

If the condition stated above is not fulfilled, the index

$$k^I = \frac{m_{15} - f_k}{s_{15}} \text{ is determined from the test results.} \quad (2.21)$$

Where $k^I \geq 2$, testing can be continued. In this case 45 further test pieces shall be taken and tested from different bars in the test unit, so that a total of 60 tests results are available ($n = 60$). The test unit shall be considered to comply with the requirements if the condition stated below is fulfilled for all properties.

$$m_{60} - 1.93 \times s_{60} > f_k \quad (2.22)$$

Where 1.93 is the value for the acceptability index, k , for $n = 60$ a failure rate of 5% ($p = 0.95$) at a probability of 90% ($1 - \alpha = 0.90$).

Poor quality control will result in a higher standard deviation (Arum and Olarewaju, 2005). British Department of Environment suggests standard deviation of 8 for results less than 40.

RESEARCH METHODOLOGY

3.1 Introduction

The site of the concrete rubbles located directly opposite Total filling station at Ifo, along Lagos-Abeokuta express way in Ogun State was surveyed and samples taken. Steel samples (used steel of known origin and used steel of unknown origin) were selected from different places at Akure, Ijare, Ile-Ife, Ilesha, Ifo and Ibadan. Original aggregate (granite) having grain size range 5.00mm to 25mm for coarse and less than 5.00mm to 150 μ m for fine was used for the control experiment in conformity with the materials of the concrete rubbles. Tests were carried out at the Geotechnical and Structural Laboratories of the Federal University of Technology, Akure, the Soil and Materials Laboratories of the Federal Polytechnic, Ado-Ekiti and Ilaro, and the Material Testing Laboratories of the Polytechnic, Ibadan. Cost of recycled materials were compared with those of new materials. This was done by asking questions from dealers of these materials.

3.2 Materials

3.2.1 Concrete rubbles

The demolished concrete rubbles shown in Plate 1 were collected from the demolition exercise carried out at Ifo in Ogun State during the construction of the Lagos-Abeokuta road dualization project.

3.2.2 Used steel

Used steel specimen shown in Plate 2 were collected randomly from Akure, Ijare, Ilesha, Ile-Ife, Ifo and Ibadan. They were used steel of known origin and used steel of unknown origin. The bar diameters are 25mm diameter, 20mm diameter, 16 mm diameter, 12mm diameter and 10mm diameter respectively. In accordance with the provisions of ISO 6935-2 (1991), eighteen (18) test pieces were taken for each diameter and fifteen (15) eventually failed within the gauge length, and were finally analysed.



Plate 1: Demolished Concrete Rubbles

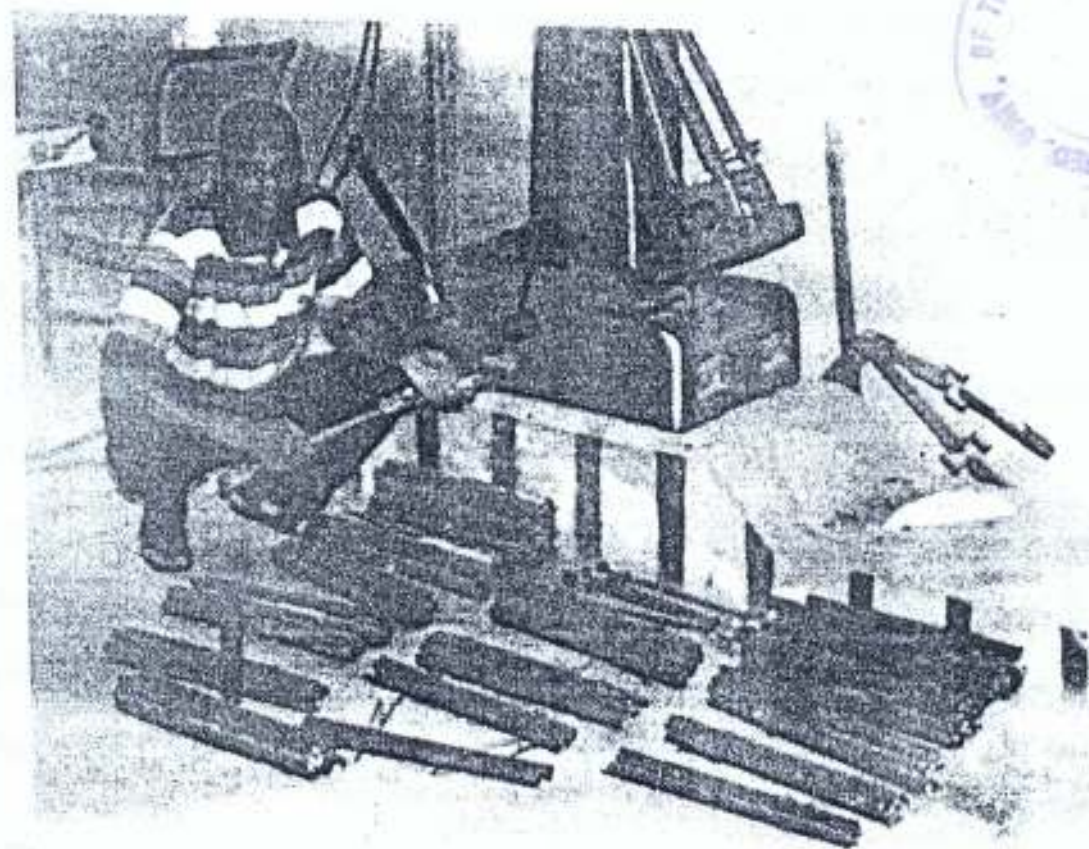


Plate 2: Steel Specimen Types

3.3 Laboratory Test of Recycled Aggregate Concrete

The laboratory tests were carried out to determine the engineering properties of recycled aggregates concrete as well as original aggregates concrete with a view to determining whether recycled aggregate could be used for the production of new concrete. Thus, the engineering properties of original aggregate concrete served as control experiment. Crushing of concrete rubbles, aggregate crushing value, workability test, compressive strength, water absorption capacity and bending strength test were carried out at the Geotechnical and Structural Laboratories of the Federal University of Technology, Akure and the Soil and Materials Laboratories of the Federal Polytechnic, Ado-Ekiti and Ilaro.

3.3.1 Crushing of demolished concrete rubbles

In this work, sledge hammer and chisel were used to break the concrete rubbles obtained from the demolition site into smaller units. But on large scale, crushing machine powered electrically or by diesel engine could be used. Preliminary sieving was then carried out to divide the recycled aggregate into coarse and fine.

3.3.2 Washing of recycled aggregate

After crushing, the recycled coarse and fine aggregates obtained from the demolition site were divided into two equal halves. One half of the recycled coarse aggregate was placed in a tank containing water for 7 days and recycled fine aggregate was equally placed in another tank containing water for the same period, after which a pair of new wire brushes were used to scrub the recycled aggregates to chip out cement paste that stuck to external part of the aggregates. After scrubbing the recycled

aggregates, it was thoroughly stirred to allow the cement remain in suspension in the water. The water with the cement in suspension was then poured out, leaving clean aggregate behind in the tank which was later scooped out and allowed to dry in the sun. Finally the clean aggregates were sieved and graded into their respective sizes.

3.3.3 Particle size distribution

The dried coarse recycled and original aggregates were graded with sieve sizes 25.4 mm, 19.0 mm, 13.2 mm, 9.5 mm and 5.0 mm while fine recycled and original aggregates were graded with sieve sizes 5.0 mm, 2.00 mm, 1.70 mm, 1.18 mm, 600 μm , 425 μm , 300 μm and 150 μm . The same grading was used for both recycled and original aggregates such that the original aggregates served as control and supervision was effective to ensure correct proportioning of constituents. The cumulative percent passing for recycled and original coarse as well as recycled and original fine aggregates were plotted on the curves indicating the limits specified in ASTM C-33 for fine aggregates and four size number (grading sizes) of coarse aggregates. At the end, the grading size of coarse recycled and original aggregates were found to be size no 67. Original aggregate (granite) was used for the control experiment in conformity with the materials of the concrete rubbles of granite composition.

3.3.4 Aggregate crushing value

Aggregate passing a 13.2 mm sieve and retained on 9.5 mm sieve was compacted in a metal cylinder of 115 mm diameter and 180 mm height internally. Each of three layers was tamped twenty-five times with a round-ended steel rod of 15 mm diameter and

600 mm length. The net weight of the filled measure was then determined. The sample was dried at 105 plus or minus 5 C for 4 hours, then cooled, weighed and similarly compacted in a cylinder (of 150 mm diameter and 135 mm height) to a depth of 100 mm over a base plate. Surfaces in contact with aggregate are of machined, case-hardened (hardness No 650 in BS 427). A load of 400 kN was applied through a plunger at the rate of 40 plus or minus 4 kN per minute. On releasing the load, the fraction passing a 2.36 mm sieve was determined. The mean of the test results were calculated and should not exceed the percentage limits shown in Table 3.1

Table 3.1 Aggregate Crushing Value Percentage Limits

Aggregate Type	Aggregate Crushing Load
Hornfels	20
Andesite; Basalt	25
Breccia; Dolerite	25
Microdiorite; Microgranite	25
Microsyenite; Rhyolite	25
Limestone; Quartzite	30
Rivergravel; Slate	30
Granite; Quartz	40

Source: Taylor (1977)

3.3.5 Specific gravities of cement and aggregates

The pycnometer was weighed empty as w_1 after which the pycnometer was filled with water until the water surface is flushed with the whole screw top. Thereafter, the

Pycnometer was dried on the outside and weighed to the nearest 0.5 gm as w_2 , the Pycnometer was then emptied and dried. About 500 gm of each sample was weighed to the nearest 0.5 gm and placed in the pycnometer and care was taken not to loose any particle. The pycnometer and each sample were weighed as w_3 . Water was added to each sample in the flask until it was about half full. The mixture was thoroughly stirred to remove air trapped in each sample. The screw top was replaced and the pycnometer filled with water. The pycnometer was shaken to remove any remaining air by holding one finger over the hole in the screw top. The pycnometer was then topped up with water. The outside of the pycnometer was dried and then weighed to the nearest 0.5 gm as w_4 . The specific gravities were then determined from these expressions,

$$\begin{aligned}
 G_s &= \frac{(w_3 - w_1)}{(w_3 - w_1) + (w_2 - w_4)} \\
 &= \frac{(w_3 - w_1)}{(w_3 + w_2) + (w_4 + w_1)} \quad (3.1)
 \end{aligned}$$

The values of the specific gravity were given to the nearest 0.01 (Bowles, 1981; Brian, 1980).

3.3.6 Workability tests

The two workability tests carried out are, **slump** test and **compacting factor** test. The slump test was carried out on each of the samples for the three types of aggregates: Original aggregate, unwashed recycled aggregate and washed recycled aggregate concrete, to determine their workabilities at water/cement ratios: 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85 and 0.90. A standard slump cone was used which was 300mm high with a bottom diameter of 200mm and a top

diameter of 100mm. All accessories were put in place before the test was carried out. The measuring outfit is shown in Plate 3. The compacting factor test became necessary because at water/cement ratios of 0.45, 0.50 and 0.55 mixes from each of original, washed recycled and unwashed recycled aggregate concretes respectively gave a zero slump indicating that they were dry mixes. The compacting factor apparatus is shown in Plate 4.

3.3.7 Water absorption capacity

Before testing the cubes, they were weighed. The difference between the weight after demoulding and weight after curing before crushing was used to determine the water absorption capacity.

3.3.8 Compressive strength: concrete mixes

The mix ratio for recycled and original aggregate concrete was 1:2:4. The standard cube size of 150mm was employed. The details of the procedures adopted for sampling, making and curing concrete cubes were in accordance with the provisions of BS 1881 (1970). The cement used was Elephant Portland Cement brand whose properties conform to BS 12. For each of the washed recycled, unwashed recycled and original aggregates concrete 3 cubes were crushed at each water/cement ratio; in the range of 0.45 to 0.90 at intervals of 0.05, at ages 7, 14 and 28 days to determine their compressive strength. In order to obtain this, the crushing load indicated on the dial of the test machine for each sample was divided by its cross sectional area and the mean strength for each aggregate concrete was obtained by dividing the sum of the compressive strength of the respective cube samples by 3.



Plate 3 Measurement of Slump



Plate 4 Compacting Factor Test

Before the cubes were crushed, they were weighed and these weights were divided by their respective volumes to give their densities. The cubes were placed in the testing machine and load was applied to opposite sides in contact with the mould during casting. The standard deviation was then calculated. Before testing the cube, they were weighed and the difference between the weight after demoulding and weight after curing was noted.

3.3.9 Bending strength

The standard dimensions for each of three beams cast for bending strength test in accordance with BS 1881 (1981) were 150mm x 150mm x 1000mm long for washed recycled and original aggregate concretes. The method of casting was similar to that of the cubes, but this time for a water-cement ratio of 0.615 for washed recycled aggregate concrete and 0.64 for original aggregate concrete. The beams were weighed after demoulding before being placed under water in the curing tank for further curing. The beams were then weighed after removal from water and then tested for bending strength after 28 days. The beam was placed in the bending testing machine with a clear distance of 750mm between the two supports. The load was then applied at the center until it failed. The load at failure was noted. The two halves were then tested for compressive strength which was used to determine the modulus of elasticity. The testing outfit is as shown in Plates 5 and 6 while the schematic diagram of the bending strength test is shown in appendix XII. All the beams tested failed within the middle third. The strength in bending is the fibre stress on the tensile side at the point of failure (Orchard, 1973).



Plate 5 : Flexural Testing of Concrete Beams

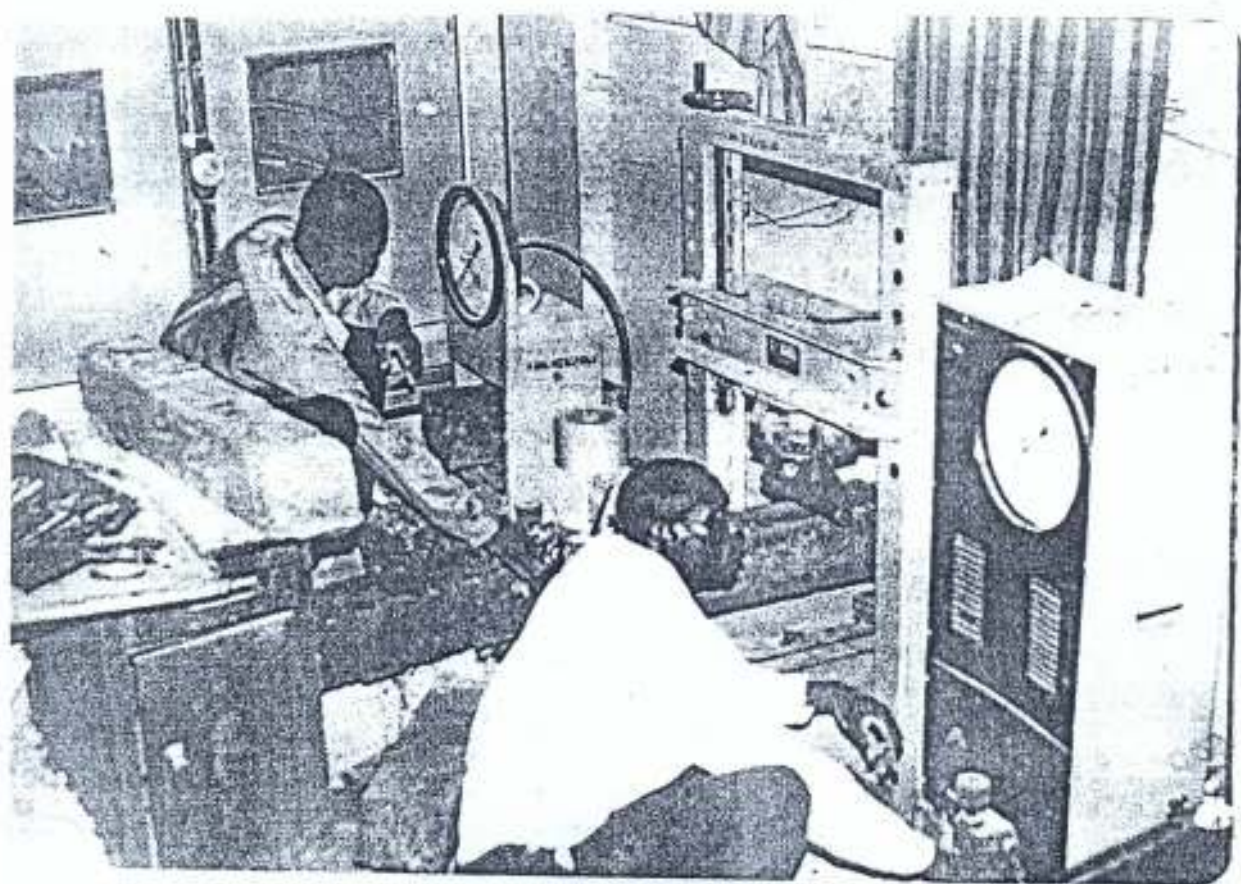


Plate 6 : Determination of Compressive Strength of the Two Halves of Failed Beams

3.4 Laboratory Test of Used Steel

Used steel specimens, that is, steel of known origin and steel of unknown origin were tested to failure under laboratory conditions. The specimens were prepared, tested and analysed in accordance with ISO 6935-2 (1991). The machine used was a universal testing machine (200 kN hydraulic) made by Avery Dimension Limited.

3.4.1 Preparation of used steel samples

The universal testing machine could not accommodate steel specimen less than 24 mm diameter so the ends of all the samples less than 24 mm diameter were welded as shown in plate 7. According to **St Venant** principle which says that if a system of forces acting on a small region of body is replaced by a different but statically equivalent system of forces acting on the same region, then such replacement does not cause significant changes in the stresses and displacements at points in the body remote from the region concerned (Fenner, 1986). In this case, for the tensile test, the end clamping and welding stresses will rapidly die out, leaving a uniform tensile stress in the middle of the specimen marked out as the gauge length within which the specimen shall fail. Each sample was 450 mm long. The gauge length for each sample was five times the diameter of each bar as specified by ISO 6935-2 (1991) and is remote from the clamped and welded ends. This was marked on each sample with the aid of scribe, ruler, hammer and center punch prior to testing.

3.4.2 Testing of used steel samples

Extensometer was attached to each specimen within the gauge length of both used steel of known origin and used steel of unknown origin as shown in Plate 8. The extensions for each load increase were noted with their corresponding diameter by using

scriber, divider, ruler and vernier caliper until failure as shown in Plates 9 and 10. As soon as the material started yielding, the extensometer was removed so as not to damage the extensometer. 15 pieces of samples for each diameter failed within the gauge length as specified by ISO 6935-2 (1991) and shown in Plate 11. Statistical analysis and equations 2.18 – 2.20 were used to determine the tensile strength, yield strength, percentage elongation and percentage reduction of area in accordance with ISO-6935-2 (1991).

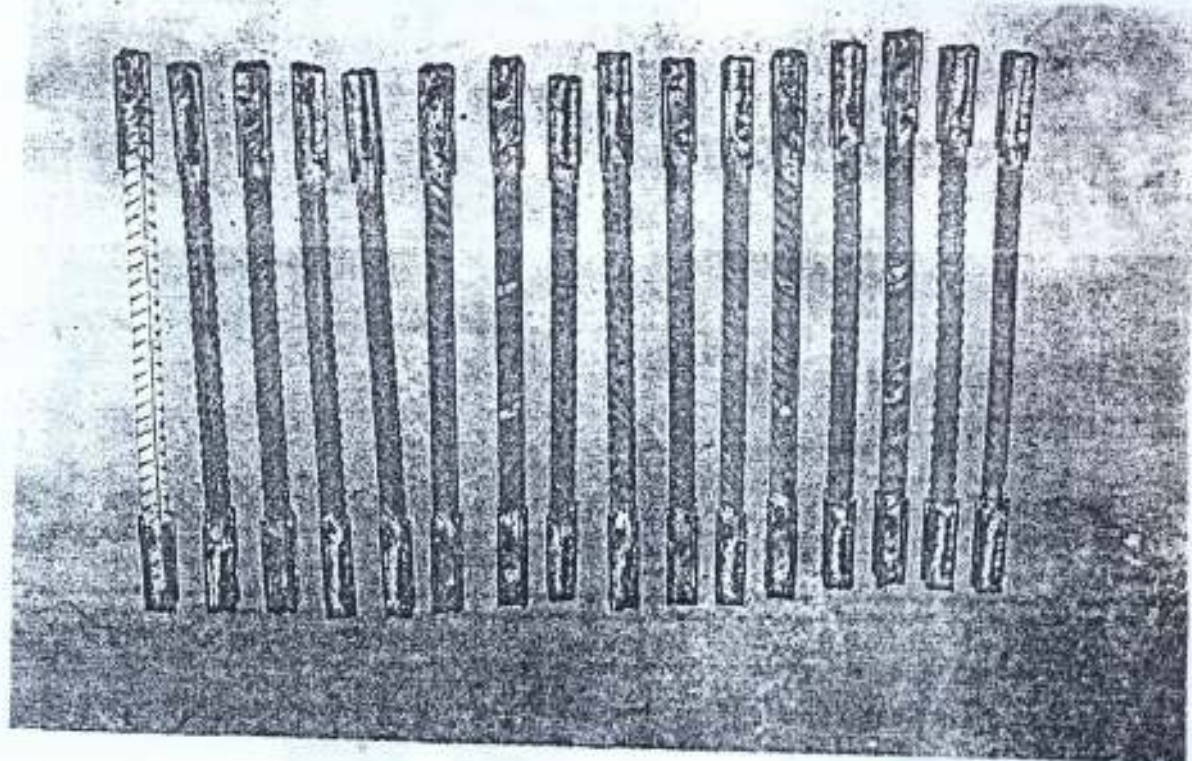


Plate 7: Welding of Specimen

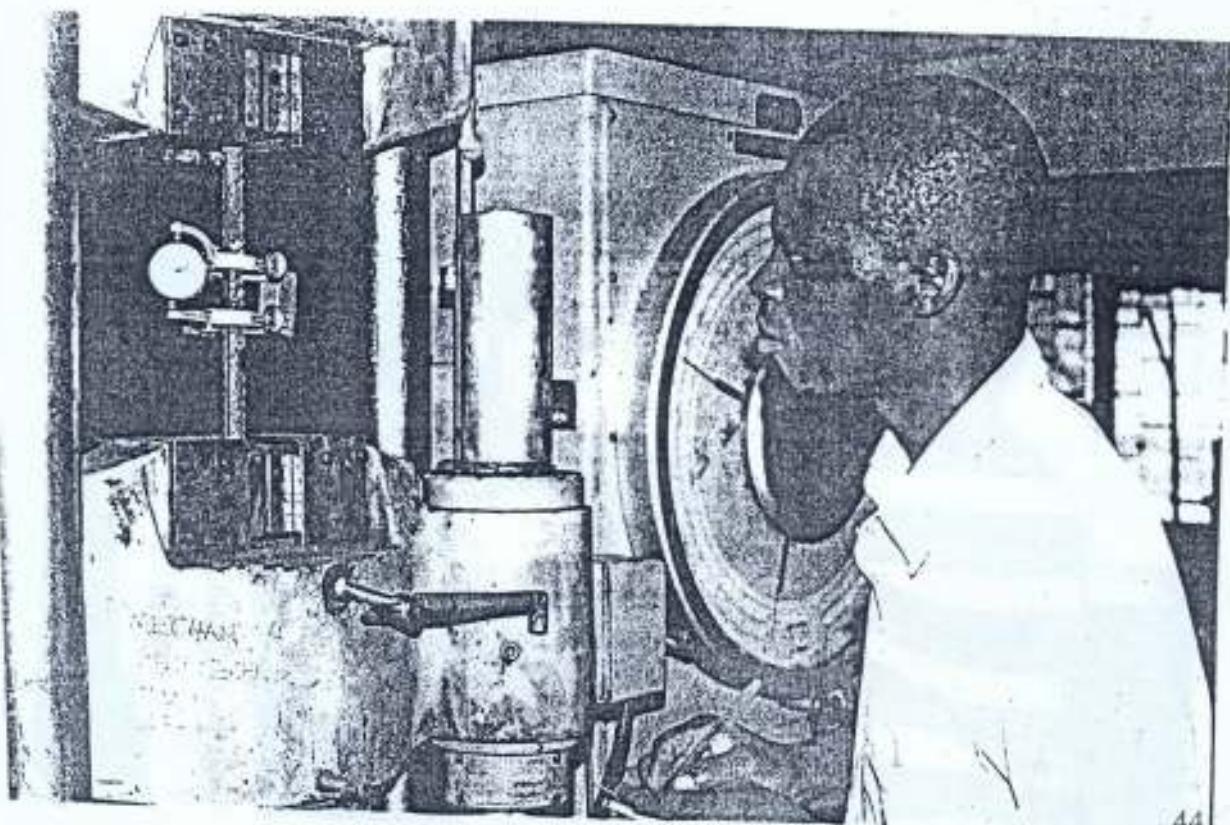


Plate 8: Testing Specimen with Extensometer

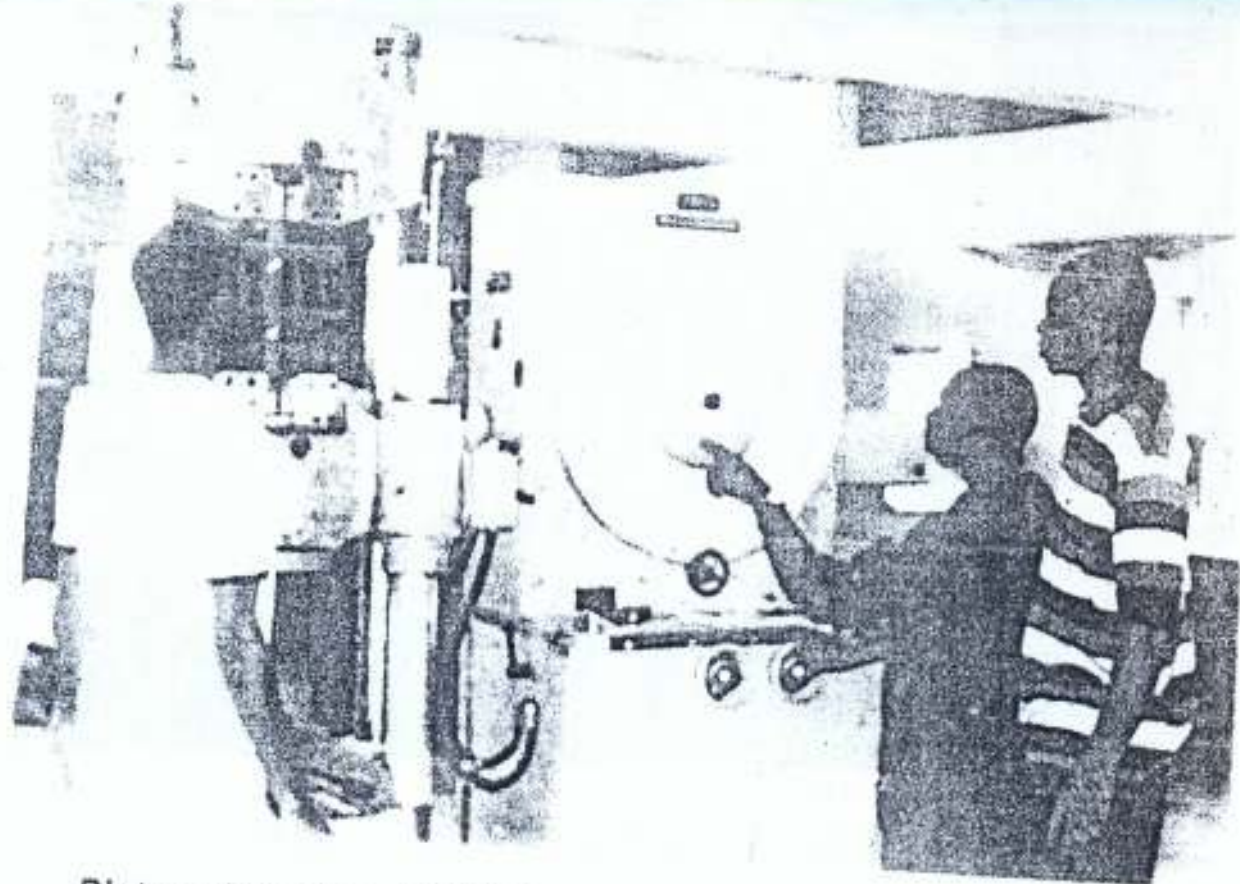


Plate 9: Reading of Dial Gauge Reading of Steel Specimen in Universal Testing Machine

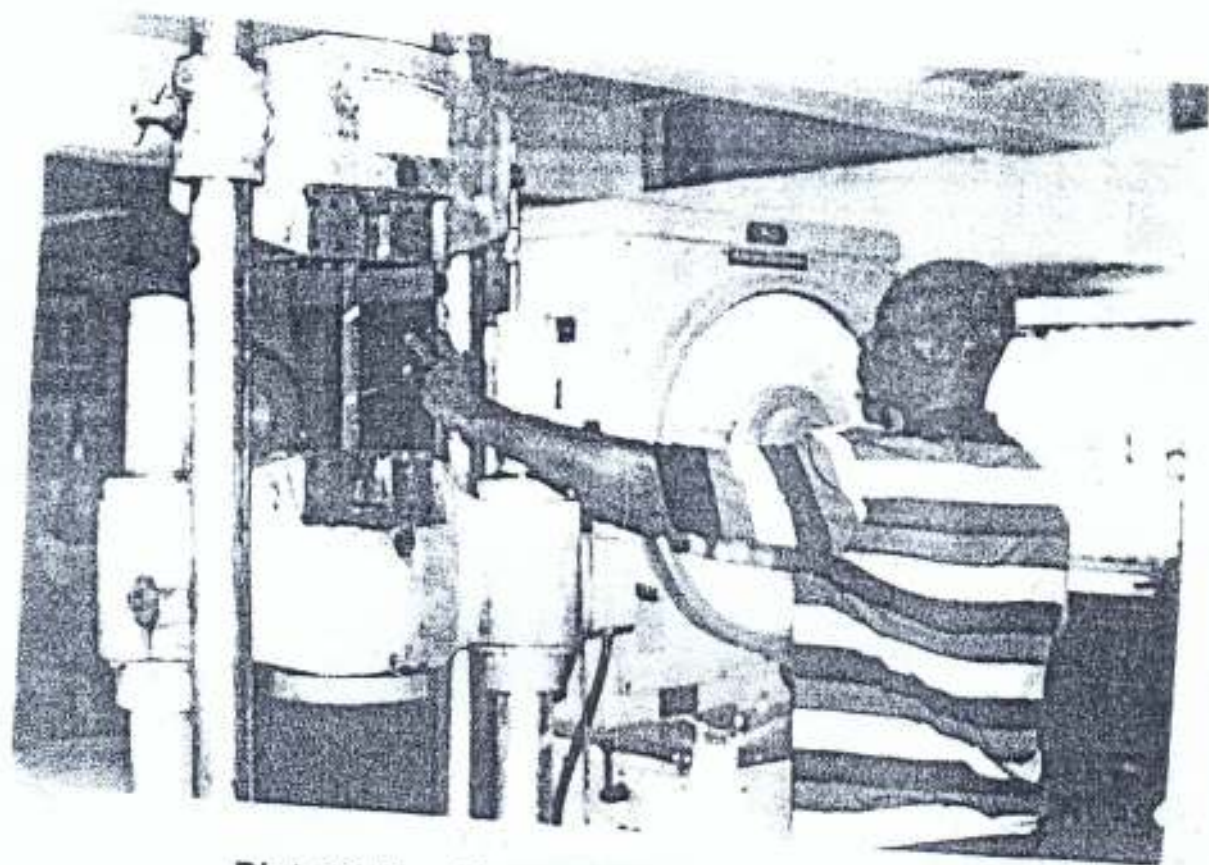


Plate 10: Tensile Testing of Steel Specimen

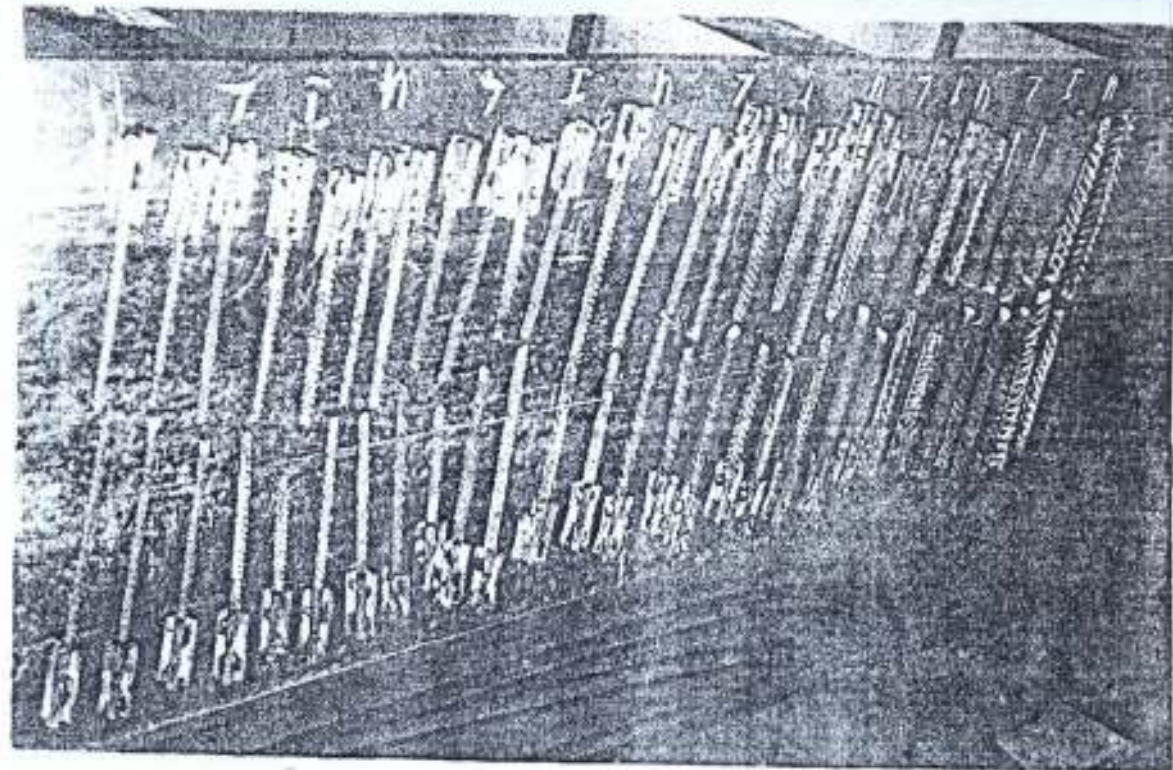


Plate 11: Failed Steel Test Specimen

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

In line with clause 3.3.3, the results of the sieve analysis for various types of aggregate used are presented in Tables 4.1 - 4.5, and the results are further graphically presented in Appendix I. The results of the aggregate crushing values for various types of aggregate are presented in Tables 4.6 - 4.8. The results of the specific gravity test are presented in Table 4.9. For the workability test on original aggregate concrete, unwashed recycled aggregate concrete and washed aggregate concrete, the results of the slump test are presented in Tables 4.10 - 4.12 while the results of compacting factor test are presented in Tables 4.13 - 4.15. The water absorption capacity results for original aggregate concrete, unwashed recycled aggregate concrete and washed recycled aggregate concrete are presented in Tables 4.16 - 4.18. The water absorption capacity values for original aggregate concrete, washed recycled aggregate concrete and unwashed recycled aggregate concrete are graphically presented in Appendixes II - IV. The results of densities and compressive strengths tests for original aggregate concrete, unwashed recycled aggregate concrete and washed recycled aggregate concrete are presented in Tables 4.19 - 4.21. The mean compressive strength values for original aggregate concrete, washed recycled aggregate concrete and unwashed recycled aggregate concrete are graphically presented in Appendixes V - VII. A summary of results of bending strength test on original aggregate concrete and washed recycled aggregate concrete are presented in Tables 4.22 (A) and 4.22 (B). The results of the representatives of all the diameters tested for used steel of known origin and used steel of unknown origin are presented in Tables 4.23 - 4.32, while the stress-strain diagrams for representative

samples of 12mm and 16mm diameters for used steel of known origin and used steel of unknown origin were plotted and shown in Appendixes VIII – XI. The results of tensile strength, yield strength, percentage elongation and percentage reduction in area (ductility constants) of steel are presented in Tables 4.33 - 4.36, the summary of the analysis that determines the engineering properties, that is, strength and ductility constants are presented in Tables 4.37(1-4) and finally the cost analysis of used steel of both known and unknown origin is shown in Table 4.38.

4.2 Discussions

Table 4.1 Grain Size Analysis for Original and Recycled Aggregate

Sieve size (inch)	Sieve size (mm)	Wt. Retained (g)	Wt. Passing (g)	% Cumul. Retained	% Cumul. Passing
1	25.4	-	21635	-	100
3/4	19.0	1193	20442	6	94
1/2	13.2	3505	16937	22	78
3/8	9.5	5236	11701	46	54
1/16	5.00	4018	7683	64	36
No.7	2.36	958	6725	69	31
No.8	2.00	350	6375	71	29
No.10	1.70	395	5950	72	28
No.14	1.18	1070	4910	77	23
No.25	0.600	1620	3290	85	15
No.36	0.425	1600	1690	93	7
No.52	0.300	240	1450	94	6
No.100	0.150	1450	-	100	-

Table 4.2 Grain Size Analysis for Original Coarse Aggregate

Sieves size(mm)	Wt. Retained (g)	Wt Passing (g)	Percentage Retained	%Cumul. Retained	% Cumul. Passing
25.4	-	14995	-	-	100
19.0	1240	13755	8	8	92
13.2	3510	10245	23	31	69
9.5	5240	5005	35	66	34
5.00	4055	950	27	93	7
2.00	950	-	8	100	-

Table 4.3 Grain Size Analysis for Original Fine Aggregate

Sieves size (mm)	Wt. Retained (g)	Wt. Retained(g)	Wt Passing(g)	% Cumul. Retained	% Cumul. Passing
5.00	-	6725	-	-	100
2.00	360	6365	5	5	95
1.70	390	5975	6	11	89
1.18	1065	4910	16	27	73
0.600	1770	3140	26	53	47
0.425	1520	1620	23	76	24
0.300	215	1405	3	79	21
0.150	1405	-	-	100	-

Table 4.4 Grain Size Analysis for Recycled Coarse Aggregate

Sieves size (mm)	Wt. Retained (g)	Wt. Passing (g)	Percentage Retained	%Cumul. Retained	% Cumul. Passing
25.4	-	14910	-	-	100
19.0	1193	13717	8	8	92
13.2	3505	10212	24	32	68
9.5	5236	4976	35	67	33
5.00	4018	958	27	94	6
2.00	958	-	6	100	-

Table 4.5 Grain Size Analysis for Recycled Fine Aggregate

Sieves size (mm)	Wt. Retained (g)	Wt. Passing (g)	Percentage Retained	% Cumul. Retained	% Cumul. Passing
5.00	-	6725	-	-	100
2.00	350	6375	5	5	95
1.70	395	5980	6	11	89
1.18	1070	4910	16	27	73
0.600	1620	3290	24	51	49
0.425	1600	1690	24	75	25
0.300	240	1450	4	79	22
0.150	1450	-	-	100	-

Table 4.6 Aggregate Crushing Values of Original Aggregate (Granite)

Weight Retained on 9.5mm Sieve (kg)	Weight Retained on 2.36 mm Sieve (kg)	Fraction Passing 2.36 mm Sieve (kg)	Aggregate Crushing Value (A.C.V) (%)
3000	2300	700	23.3
3000	2370	630	21
3000	2340	660	22
Average			22.1

Table 4.7 Aggregate Crushing Values of Unwashed Recycled Aggregate

Weight Retained on 9.5mm Sieve (kg)	Weight Retained on 2.36 mm Sieve (kg)	Fraction Passing 2.36 mm Sieve (kg)	Aggregate Crushing Value (A.C.V) (%)
3000	2100	900	30
3000	2040	960	31
3000	1980	1020	34
Average			32

Table 4.8 Aggregate Crushing Values of Washed Recycled Aggregate

Weight Retained on 9.5mm Sieve (kg)	Weight Retained on 2.36 mm Sieve (kg)	Fraction Passing 2.36 mm Sieve (kg)	Aggregate Crushing Value (A.C.V) (%)
3000	2250	750	25
3000	2280	720	24
3000	2220	780	26
Average			25

Table 4.9 Results of Specific Gravity Test

Specimen	Weight of empty pycnometer w_1 (g)	Weight of Pycnometer + water full w_2 (g)	Weight of Specimen + pycnometer w_3 (g)	Weight of Specimen + water full + pycnometer, w_4 (g)	Specific gravity, G
Portland Cement	221	1309	609	1575	3.18
Unwashed Recycled Aggregate	180	4789	2908	6405	2.45
Washed recycled Aggregate	180	4789	2918	6459	2.56
Original Aggregate	180	4789	2936	6486	2.60

4.2.1 Aggregate Crushing Value

From the result of this work, the average crushing value of original, unwashed recycled and washed recycled aggregates are 22.1, 32 and 25 respectively. Removal of cement paste from the recycled aggregate has reduced the aggregate crushing value and there is a degree of similarity in the aggregate crushing value of original and washed recycled aggregate.

4.2.2 Specific gravities

From the results of this work, Portland cement, unwashed recycled aggregate, washed recycled aggregate and original aggregate (granite) have specific gravities 3.18, 2.45, 2.56 and 2.60 respectively. These results are in agreement with the results of Ola (1983), Ozelton and Baird (1976) and Potter(1985). It is evident from the above results that cement paste adhering to the recycled aggregate lowers its specific gravity.



Table 4.10 Slump Test Results for Original Aggregate Concrete

Mix Proportion	Water-Cement Ratio	Slump, (mm)	Types of Slump
1:2:4	0.40	0	Zero
1:2:4	0.45	0	Zero
1:2:4	0.50	3	True
1:2:4	0.55	3	True
1:2:4	0.60	5	True
1:2:4	0.65	9	True
1:2:4	0.70	25	Shear
1:2:4	0.75	30	Shear
1:2:4	0.80	-	Collapse

Table 4.11 Slump Test Results for Unwashed Recycled Aggregate Concrete

Mix Proportion	Water-Cement ratio	Slump, (mm)	Types of Slump
1:2:4	0.55	0	Zero
1:2:4	0.60	4	True
1:2:4	0.65	4	True
1:2:4	0.70	5	True
1:2:4	0.75	6	True
1:2:4	0.80	9	Shear
1:2:4	0.90	35	Collapse
1:2:4	1.00	-	

Table 4.12 Slump Test Results for Washed Recycled Aggregate Concrete

Mix Proportion	Water-Cement Ratio	Slump, (mm)	Types of Slump
1:2:4	0.45	0	Zero
1:2:4	0.50	0	Zero
1:2:4	0.55	4	True
1:2:4	0.60	5	True
1:2:4	0.65	7	True
1:2:4	0.70	8	True
1:2:4	0.75	30	True
1:2:4	0.80	-	Shear
1:2:4	0.85	-	Shear
1:2:4	0.90	-	Collapse

Table 4:13 Result of Compacting Factor Test for Original Aggregate Concrete

Mix Proportion	Water-ratio	Cement	Weight of Partially Compacted Concrete W_1 (g)	Weight of fully Compacted Concrete W_2 (g)	Compacting Factor W_1/W_2
1:2:4	0.45		8530	10700	0.80
1:2:4	0.50		9100	11200	0.81
1:2:4	0.55		9300	11210	0.83
1:2:4	0.60		9600	11300	0.85
1:2:4	0.65		9900	11400	0.87
1:2:4	0.70		10200	11500	0.89
1:2:4	0.75		10600	11650	0.91
1:2:4	0.80		11100	11800	0.94

Table 4.14 Result of Compacting Factor Test for Unwashed Recycled Aggregate Concrete

Mix Proportion	Water-ratio	Cement	Weight of Partially Compacted Concrete W_1 (g)	Weight of fully Compacted Concrete W_2 (g)	Compacting Factor W_1/W_2
1:2:4	0.55		7500	9900	0.76
1:2:4	0.60		7400	9500	0.78
1:2:4	0.65		7800	9870	0.79
1:2:4	0.70		8100	9750	0.83
1:2:4	0.75		9000	10070	0.84
1:2:4	0.80		9100	10700	0.85
1:2:4	0.90		9700	10400	0.93
1:2:4	1.00		10600	10900	0.97

Table 4.15 Result of Compacting Factor Test for Washed Recycled Aggregate Concrete

Mix Proportion	Water-ratio	Cement	Weight of Partially Compacted Concrete W_1 (g)	Weight of fully Compacted Concrete W_2 (g)	Compacting Factor W_1/W_2
1:2:4	0.45		8450	10800	0.78
1:2:4	0.50		8700	11000	0.79
1:2:4	0.55		9100	11200	0.81
1:2:4	0.60		9500	11200	0.83
1:2:4	0.65		9700	11400	0.85
1:2:4	0.70		9900	11400	0.87
1:2:4	0.75		10300	11500	0.90
1:2:4	0.80		10600	11800	0.92

Weight of empty cylinder = 3630g

4.2.3 Workability

The results of the slump test and compacting factor test showed that washed recycled aggregate concrete is more workable than unwashed recycled aggregate concrete. The main factor of workability is the water content of the mix. If the water content is fixed, workability is governed by the maximum size of aggregate, its grades, shape and texture (Taylor, 1977). Washed recycled aggregate concrete compares favourably well with original aggregate concrete in terms of workability. In addition, the results also showed that washed recycled aggregate concrete responds favourably to compaction similar to original aggregate concrete, while unwashed recycled aggregate concrete needs more effort in order to be fully compacted. This is due to the fact that cement paste adhering to the unwashed recycled aggregate has absorbed much of the water needed for workability and the surface of the unwashed recycled aggregate is not smooth to allow the aggregate to slide over one another during compaction (Arum and Tanimola, 2005).

Table 4.16 Water Absorption Capacity for Original Aggregate Concrete

Water-cement (w/c) Ratio	Density (kg/m ³)	Water Absorption Capacity (%)
0.45	2410	2.05
0.50	2504	0.95
0.55	2464	0.90
0.60	2449	0.80
0.65	2415	0.65
0.70	2381	0.51
0.75	2372	0.49
0.80	2366	0.45

Table 4.17 Water Absorption Capacity for Unwashed Recycled Aggregate Concrete

Water-cement (w/c) Ratio	Density (kg/m ³)	Water Absorption Capacity (%)
0.50	1873	4.00
0.55	2015	3.10
0.60	2263	1.75
0.65	2343	1.15
0.70	2316	1.10
0.75	2311	1.07
0.80	2235	1.04
0.90	2219	1.80
1.00	2180	1.63

Table 4.18 Water Absorption Capacity for Washed Recycled Aggregate Concrete

Water-cement (w/c) Ratio	Density (kg/m ³)	Water Absorption Capacity (%)
0.55	2372	1.95
0.60	2380	1.60
0.65	2410	1.06
0.70	2400	0.75
0.75	2383	0.53
0.80	2375	0.45
0.90	2356	0.38
1.00	2331	0.34

4.2.4 Water absorption capacity

Based on the results of the present work, water absorption capacity of original aggregate concrete is similar to that of washed recycled aggregate concrete because the cement paste has been removed by washing. In addition to this, it was seen that as the water-cement ratio increases by 0.05, percentage water absorption capacity reduces by about 10%. In the case of washed recycled aggregate concrete and original aggregate concrete, the water absorption capacity and density relationship is similar as it can be seen that as the density of the concrete reduces, water absorption capacity reduces. This is due to the fact that compaction is better achieved in washed recycled aggregate concrete which produces dense, well compacted concrete. On the other hand, unwashed recycled aggregate concrete has a higher water absorption capacity ranging from 4.00% to 1.63% for water-cement ratios ranging from 0.50 to 1.00 due to the presence of cement mortar adhered to the aggregate which has absorbed more water needed for workability. Furthermore, in unwashed recycled aggregate concrete, water absorption capacity and density relationship is parabolic, meaning that as the density increases, water absorption capacity increases. This agrees with the submission of Neil and Ravindra (1996), Neville (1981) and Kreijer (1983).

Table 4.19 Densities and Compressive Strength of Original Aggregate Concrete

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.45	06/06/05	13/6/05	7	8100	8133	2410	675	675	30.00	6.16
	C ₂	0.45				8200			685			
	C ₃	0.45				8100			665			
	C ₁	0.50	06/06/05	13/6/05		8500	8450	2504	592	595	26.44	1.25
	C ₂	0.50				8400			595			
	C ₃	0.50				8450			593			
	C ₁	0.55	07/06/05	14/6/05		8250	8317	2464	490	492	21.87	6.24
	C ₂	0.55				8300			485			
	C ₃	0.55				8400			500			
	C ₁	0.60	07/06/05	14/6/05		8200	8270	2449	300	305	17.56	4.08
	C ₂	0.60				8300			305			
	C ₃	0.60				8300			310			
	C ₁	0.65	08/06/05	15/6/05		8100	8150	2415	292	292	14.99	2.05
	C ₂	0.65				8200			290			
	C ₃	0.65				8150			295			
	C ₁	0.70	08/06/05	15/6/05		8050	8037	2381	278	280	12.44	1.70
	C ₂	0.70				8020			282			
	C ₃	0.70				8040			281			
	C ₁	0.75	09/06/05	16/6/05		8010	8007	2372	205	204	9.05	2.62
	C ₂	0.75				8000			200			
	C ₃	0.75				8010			206			
	C ₁	0.80	09/06/05	16/6/05		8010	8007	2372	205	204	9.05	2.62
	C ₂	0.80				8000			200			
	C ₃	0.80				8010			206			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.19 Contd.

Mix Proportion	Cube Number	Water-cement (w/c) ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.45	06/06/05	13/6/05	14	8150	8167	2420	815	810	36.00	4.08
	C ₂	0.45				8100			810			
	C ₃	0.45				8250			805			
	C ₁	0.50	06/06/05	13/6/05		8450	8467	2507	705	705	31.33	0.47
	C ₂	0.50				8600			704			
	C ₃	0.50				8350			705			
	C ₁	0.55	07/06/05	14/6/05		8200	8283	2454	520	515	22.89	4.08
	C ₂	0.55				8300			515			
	C ₃	0.55				8350			510			
	C ₁	0.60	07/06/05	14/6/05		8210	8267	2449	400	405	18.00	4.08
	C ₂	0.60				8280			405			
	C ₃	0.60				8310			410			
	C ₁	0.65	08/06/05	15/6/05		8080	8157	2417	393	391	17.38	1.63
	C ₂	0.65				8220			391			
	C ₃	0.65				8170			389			
	C ₁	0.70	08/06/05	15/6/05		8020	8030	2379	387	385	17.11	2.16
	C ₂	0.70				8040			382			
	C ₃	0.70				8030			386			
	C ₁	0.75	09/06/05	16/6/05		7980	8003	2371	305	301	13.38	4.19
	C ₂	0.75				8020			295			
	C ₃	0.75				8010			302			
	C ₁	0.80	09/06/05	16/6/05		8010	7987	2366	265	261	11.60	3.30
	C ₂	0.80				7980			260			
	C ₃	0.80				7970			257			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.19 Contd.

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.45	20/6/05	18/07/05	28	8250	8183	2425	970	975	43.30	4.11
	C ₂	0.45				8150			980			
	C ₃	0.45				8150			974			
	C ₁	0.50	20/6/05	18/07/05		8400	8400	2489	855	850	37.80	4.11
	C ₂	0.50				8450			845			
	C ₃	0.50				8350			851			
	C ₁	0.55	21/6/05	19/07/05		8200	8267	2449	770	762	33.88	6.13
	C ₂	0.55				8250			762			
	C ₃	0.55				8350			755			
	C ₁	0.60	21/6/05	19/07/05		8250	8250	2444	638	640	28.40	2.36
	C ₂	0.60				8350			643			
	C ₃	0.60				8150			638			
	C ₁	0.65	22/6/05	20/07/05		8250	8133	2410	572	568	25.26	2.87
	C ₂	0.65				8100			568			
	C ₃	0.65				8050			565			
	C ₁	0.70	22/6/05	20/07/05		8040	8023	2377	475	470	20.90	4.08
	C ₂	0.70				8010			465			
	C ₃	0.70				8020			470			
	C ₁	0.75	23/6/05	21/07/05		7990	8003	2371	400	405	18.00	4.08
	C ₂	0.75				8010			410			
	C ₃	0.75				8010			405			
	C ₁	0.80	23/6/05	21/07/05		7980	7983	2365	330	320	14.20	6.16
	C ₂	0.80				7960			320			
	C ₃	0.80				8010			310			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.20 Densities and Compressive Strength of Unwashed Recycled Aggregate Concrete

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.60	07/06/05	14/06/05	7	7680	7657	2269	290	312	13.87	15.46
	C ₂	0.60				7640			320			
	C ₃	0.60				7650			325			
	C ₁	0.65	08/06/05	15/06/05		7910	7903	2342	295	292	12.98	8.50
	C ₂	0.65				7860			280			
	C ₃	0.65				7940			300			
	C ₁	0.70	08/06/05	15/06/05		7880	7843	2324	220	230	10.22	8.16
	C ₂	0.70				7840			240			
	C ₃	0.70				7810			230			
	C ₁	0.75	09/06/05	16/06/05		7990	7800	2350	173	180	8.00	5.10
	C ₂	0.75				7800			185			
	C ₃	0.75				7810			182			
	C ₁	0.80	09/06/05	16/06/05		7540	7517	2230	148	143	6.36	5.72
	C ₂	0.80				7550			146			
	C ₃	0.80				7490			135			
	C ₁	0.90	10/06/05	17/06/05		7540	7490	2219	118	113	5.06	3.77
	C ₂	0.90				7460			110			
	C ₃	0.90				7470			110			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.20 Contd.

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.60	14/06/05	28/06/05	14	7600	7633	2262	382	383	17.02	3.40
	C ₂	0.60				7620			380			
	C ₃	0.60				7680			388			
	C ₁	0.65	15/06/05	29/06/05		7880	7900	2341	338	341	15.16	3.40
	C ₂	0.65				7900			340			
	C ₃	0.65				7920			346			
	C ₁	0.70	15/06/05	29/06/05		7880	7843	2324	279	274	12.18	3.86
	C ₂	0.70				7810			270			
	C ₃	0.70				7840			272			
	C ₁	0.75	16/06/05	30/06/05		7800	7810	2314	220	224	9.94	2.87
	C ₂	0.75				7820			227			
	C ₃	0.75				7810			224			
	C ₁	0.80	16/06/05	30/06/05		7510	7520	2228	172	174	7.73	2.83
	C ₂	0.80				7550			178			
	C ₃	0.80				7500			172			
	C ₁	0.90	17/06/05	01/07/05		7480	7480	2216	130	133	5.93	3.40
	C ₂	0.90				7500			138			
	C ₃	0.90				7460			132			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3.

Table 4.20 Contd.

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.60	21/06/05	19/07/05	28	7620	7637	2263	440	443	19.70	12.47
	C ₂	0.60				7680			460			
	C ₃	0.60				7610			430			
	C ₁	0.65	22/06/05	20/07/05		7890	7906	2343	378	382	16.98	4.32
	C ₂	0.65				7920			388			
	C ₃	0.65				7910			380			
	C ₁	0.70	22/06/05	20/07/05		7810	7817	2316	310	314	13.96	3.30
	C ₂	0.70				7830			318			
	C ₃	0.70				7810			315			
	C ₁	0.75	23/06/05	21/07/05		7820	7800	2311	260	255	11.33	4.11
	C ₂	0.75				7790			250			
	C ₃	0.75				7790			254			
	C ₁	0.80	23/06/05	21/07/05		7540	7543	2235	205	205	9.11	4.08
	C ₂	0.80				7510			200			
	C ₃	0.80				7580			210			
	C ₁	0.90	24/06/05	22/07/05		7460	7490	2219	164	167	7.42	3.77
	C ₂	0.90				7520			172			
	C ₃	0.90				7490			164			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.21 Densities and Compressive Strength of Washed Recycled Aggregate Concrete

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.55	07/06/05	14/6/05	7	7900	8000	2370	475	485	21.56	5.07
	C ₂	0.55				8100			490			
	C ₃	0.55				8000			490			
	C ₁	0.60	07/06/05	14/6/05		8010	8033	2380	390	393	17.97	2.62
	C ₂	0.60				7990			391			
	C ₃	0.60				8100			396			
	C ₁	0.65	08/06/05	15/6/05		8150	8150	2415	345	341	15.14	3.30
	C ₂	0.65				8100			337			
	C ₃	0.65				8200			340			
	C ₁	0.70	08/06/05	15/6/05		8100	8107	2402	284	282	12.53	0.94
	C ₂	0.70				8050			286			
	C ₃	0.70				8170			286			
	C ₁	0.75	09/06/05	16/6/05		8000	8040	2384	234	236	10.49	2.49
	C ₂	0.75				8100			236			
	C ₃	0.75				8040			240			
	C ₁	0.80	09/06/05	16/6/05		8020	8020	2376	170	169	7.51	0.94
	C ₂	0.80				8040			170			
	C ₃	0.80				8000			168			
	C ₁	0.90	10/06/05	17/06/05		7950	7933	2351	152	150	6.67	1.63
	C ₂	0.90				7900			148			
	C ₃	0.90				7950			150			
	C ₁	1.00	10/06/05	17/06/05		7850	7850	2326	134	133	5.91	2.16
	C ₂	1.00				7900			135			
	C ₃	1.00				7800			130			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.21 Contd.

Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive Strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2:4	C ₁	0.55	14/06/05	28/6/05	14	8150	8017	2375	600	593	26.36	8.99
	C ₂	0.55				7850			580			
	C ₃	0.55				8050			598			
	C ₁	0.60	14/06/05	28/6/05		8100	8097	2384	510	505	22.44	4.08
	C ₂	0.60				8050			505			
	C ₃	0.60				7990			500			
	C ₁	0.65	15/06/05	29/6/05		8150	8137	2411	410	407	18.07	2.36
	C ₂	0.65				8110			405			
	C ₃	0.65				8150			405			
	C ₁	0.70	15/06/05	29/6/05		8060	8120	2406	355	362	16.07	4.24
	C ₂	0.70				8120			360			
	C ₃	0.70				8180			370			
	C ₁	0.75	16/06/05	30/6/05		8020	8030	2379	290	292	12.96	2.36
	C ₂	0.75				8040			295			
	C ₃	0.75				8030			290			
	C ₁	0.80	16/06/05	30/6/05		8010	8017	2375	235	236	10.49	3.30
	C ₂	0.80				8010			232			
	C ₃	0.80				8030			240			
	C ₁	0.90	17/06/05	31/06/05		7980	7930	2350	170	166	7.39	2.62
	C ₂	0.90				7900			164			
	C ₃	0.90				7910			165			
	C ₁	1.00	17/06/05	31/06/05		7840	7853	2327	148	149	6.64	3.40
	C ₂	1.00				7810			146			
	C ₃	1.00				7910			154			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

Table 4.21 Contd.

Table 4.21 Contd.												
Mix Proportion	Cube Number	Water-cement (w/c) Ratio	Date		Age (Days)	Weight of cubes (g)	Average weight of cubes (g)	Average Density kg/m ³	Crushing load (kN)	Average Crushing load (kN)	Compressive strength (N/mm ²)	Standard Deviation (N/mm ²)
			Cast	Crushed								
1:2: 4	C ₁	0.55	21/06/05	19/07/05	28	7890	8007	2372	690	707	31.41	5.89
	C ₂	0.55				8110			720			
	C ₃	0.55				8020			710			
	C ₁	0.60	21/06/05	19/07/05		8050	8033	2380	600	600	26.7	6.16
	C ₂	0.60				7950			590			
	C ₃	0.60				8100			610			
	C ₁	0.65	22/06/05	20/07/05		8120	8133	2410	505	507	22.53	4.24
	C ₂	0.65				8180			515			
	C ₃	0.65				8100			500			
	C ₁	0.70	22/06/05	20/07/05		8140	8097	2399	410	410	18.22	4.50
	C ₂	0.70				8000			405			
	C ₃	0.70				8150			416			
	C ₁	0.75	23/06/05	21/07/05		8100	8043	2383	362	359	15.96	2.94
	C ₂	0.75				8020			355			
	C ₃	0.75				8010			360			
	C ₁	0.80	23/06/05	21/07/05		8010	8017	2375	295	302	13.42	6.24
	C ₂	0.80				8020			310			
	C ₃	0.80				8020			300			
	C ₁	0.90	24/06/05	22/07/05		8000	7953	2356	246	242	10.76	2.83
	C ₂	0.90				7960			240			
	C ₃	0.90				7900			240			
	C ₁	1.00	24/06/05	22/07/05		7900	7867	2331	182	181	8.04	0.94
	C ₂	1.00				7800			180			
	C ₃	1.00				7900			180			

Legend; C₁ = Cube 1, C₂ = Cube 2 and C₃ = Cube 3

4.2.5 Densities

From the results, it was observed that the average densities of original aggregate concrete are similar to that of washed recycled aggregate concrete. Average densities of original aggregate concrete range from 2449 kg/m^3 for 0.55 water – cement ratio to 2365 kg/m^3 for 0.80 water cement ratio which is in agreement with Shacklock (1974) and Lyndon and Kenneth (1979) while washed recycled aggregate concrete has average densities ranging from 2375 kg/m^3 for 0.55 water cement ratio to 2376 kg/m^3 for 0.80 water – cement ratio. On the other hand, the average densities of unwashed recycled aggregate concrete ranges from 2262 kg/m^3 for 0.60 water – cement ratio to 2216 kg/m^3 for 0.90 water – cement ratio. This is due to the fact that, removal of attached cement paste from the recycled aggregates made it possible and easier to compact the concrete to produce a more dense concrete. In addition to the foregoing, the results indicate that the densities of unwashed recycled aggregate concrete are lower than that of original aggregate concrete and washed recycled aggregate concrete. This is in agreement with the assertion of Hansen and Naruds (1983), Hansen (1992) and B.C.S.J (1978).

4.2.6 Compressive strength

From the results of this work, it is evident that the average compressive strength of washed recycled aggregate concrete at 7 days ranges from 21.56 N/mm^2 for 0.55 water cement ratio to 5.91 N/mm^2 for 1.00 water – cement ratio, at 14 days, from 26.36 N/mm^2 for 0.55 water cement ratio to 6.64 N/mm^2 for 1.00 water – cement ratio and at 28 days, from 31.41 N/mm^2 for 0.55 water – cement ratio to 8.04 N/mm^2 for 1.00 water – cement ratio. These results are close to that of original aggregate concrete, and it is in agreement with the results of Shacklock (1974). On the other hand, the average compressive strength

of unwashed recycled aggregate concrete is lower and it ranges from 13.87 N/mm^2 for 0.60 water – cement ratio to 5.06 N/mm^2 for 0.90 water – cement ratio at 7 days, while at 14 days, it ranges from 17.02 N/mm^2 for 0.60 water – cement ratio to 5.93 N/mm^2 for 0.90 water – cement ratio and at 28 days, it ranges from 19.70 N/mm^2 for 0.60 water – cement ratio to 7.42 N/mm^2 for 0.90 water – cement ratio. These are in close agreement with the conclusions of Nixon (1978), B.C.S.J (1978), Hansen and Narud (1983) and Arum and Tanimola (2005). In addition to the foregoing, compressive strength results showed that at water-cement ratios considered, the strength of unwashed recycled aggregate concrete at various crushing ages investigated is appreciably lower than the strength of original aggregate concrete and washed recycled aggregate concrete, while at the water-cement ratios considered, the strength of the original aggregate concrete is similar to that of the washed recycled aggregate concrete. This is further illustrated in Appendixes V - VII.



Table 4.22(A) Bending Strength of Original Aggregate Concrete

Specimen Number	Mix Proportion	Water-cement (w/c) ratio	Date		Age (Days)	Weight of beam (kg)	Load (kN)	Bending strength $M=\frac{WL}{bd^2}$ (N/mm ²)	Crushing load of two halves (kN)	Compressive strength N/mm ²
			Cast	Tested						
BSB 1	1:2:4	0.64	08/09/05	06/10/05	28	58.3	16.80	3.77 570 567 572 560	25.33 25.20 25.42 24.89	
BSB 2		0.64	08/09/05	06/10/05		58.5	17.05	3.79 575 565 562 573	25.56 25.11 24.98 25.47	
BSB 3		0.64	08/09/05	06/10/05		58.2	17.10	3.80 580 570 565 566	25.78 25.33 25.11 25.16	
Average								AV=3.77		AV=25.28

Standard Deviation

0.012N/mm²

0.24 N/mm²

Legend;

BSB 1 – Bending Strength Beam 1

BSB 2 – Bending Strength Beam 2

BSB 3 – Bending Strength Beam 3

Table 4.22 (B) Bending Strength of Washed Recycled Aggregate Concrete

Specimen Number	Mix Proportion	Water-cement (w/c) ratio	Date		Age (Days)	Weight of beam (kg)	Load (kN)	Bending strength $M=\frac{WL}{bd^2}$ (N/mm ²)	Crushing load of two halves (kN)	Compressive strength (N/mm ²)
			Cast	Tested						
BSB 1	1:2:4	0.615	08/09/05	06/10/05	28	58.1	17.00	3.78	582 572 568 570	25.87 25.42 25.24 25.33
BSB 2		0.615	08/09/05	06/10/05		58.2	16.65	3.70	571 580 575 565	25.38 25.78 25.56 25.11
BSB 3		0.615	08/09/05	06/10/05		58.0	16.85	3.74	582 568 572 565	25.87 25.24 25.42 25.11
		Average						AV=3.74		AV=25.36

Standard Deviation

0.03 N/mm²

0.26 N/mm²

Legend;

BSB 1 – Bending Strength Beam 1

BSB 2 – Bending Strength Beam 2

BSB 3 – Bending Strength Beam 3

4.2.7 Bending strength

Based on the results of this work, the average bending strength of washed recycled aggregate concrete and original aggregate concrete are 3.74 N/mm^2 and 3.77 N/mm^2 respectively while standard deviation values of the bending strength of washed recycled aggregate and original aggregate concrete are 0.03 N/mm^2 and 0.012 N/mm^2 respectively. There is high degree of similarity in the two results because of the low standard deviation. The results are in agreement with the results of Shacklock (1974), Road Research Technical Paper No. 67 and Lydon (1979).

4.2.8 Statistical analysis

From the results of the statistical analysis of compressive strength values of concrete, the standard deviation is less than the value of 8 suggested by the British Department of Environment for less than 40 results. The standard deviation of compressive strength of unwashed recycled aggregate concrete is high at low water – cement ratio, because it is almost impossible to achieve uniform compaction at low water-cement ratio but this is not so in the case of washed recycled aggregate concrete which has low standard deviation. Washed recycled aggregate concrete showed similar characteristics with original aggregate concrete (Neville, 1981), (Lydon, 1979) and (Murdock and Brook, 1979).

4.2.9 Modulus of elasticity of (E_c) concrete

Modulus of Elasticity of Original and Washed Recycled Aggregate Concrete:

From Appendixes V and VI, for compressive strength of 25 N/mm^2 for original aggregate concrete with water – cement ratio of 0.64, the corresponding water – cement ratio of washed recycled aggregate concrete is 0.615 with compressive strength of 25 N/mm^2 .

Average weight of original aggregate concrete (control) = 8200kg

Average compressive strength of original aggregate concrete (control), f_c
= 25.38 N/mm^2

Average weight of washed recycled aggregate concrete = 8100 kg

Average compressive strength of washed recycled aggregate concrete, f_c
= 25.28 N/mm^2

Average density of original aggregate concrete,

$$= \frac{8200 \times 9.81}{0.15^3 \times 1000 \times 1000} = 23.83 \text{ N/mm}^3$$

Average density of washed recycled aggregate concrete,

$$= \frac{8100 \times 9.81}{0.15^3 \times 1000 \times 1000} = 23.54 \text{ N/mm}^3$$

Using Equation 2.3

Modulus of Elasticity of Concrete;

$$E_c = 2.1 \times 10^5 \times \left[\frac{\alpha}{2.3} \right]^{1.5} \times \sqrt{(f_c / 200)}$$

E_c (Original aggregate concrete, Control)

$$\begin{aligned} E_c &= 2.1 \times 10^5 \times \left[\frac{23.83}{2.3} \right]^{1.5} \times \sqrt{(25.38/200)} \times 10^{-5} \\ &= 2.1 \times 10^5 \times 33.35 \times 0.356 \times 10^{-5} \\ &= 24.93 \text{ kN/mm}^2 \end{aligned}$$

E_c (Washed recycled aggregate concrete)

$$\begin{aligned} E_c &= 2.1 \times 10^5 \times \left[\frac{23.54}{2.3} \right]^{1.5} \times \sqrt{(25.38/200)} \times 10^{-5} \\ &= 2.1 \times 10^5 \times 32.743 \times 0.35553 \times 10^{-5} \\ &= 24.45 \text{ kN/mm}^2 \end{aligned}$$

Range of Modulus of Elasticity of Concrete E_c for compressive strength of 25 N/mm² is 22 – 30 kN/mm² with an average of 26 kN/mm² (Shacklock, 1974). The results of the compressive strength gave the modulus of elasticity of washed recycled aggregate concrete as 24.45 kN/mm² while that of original aggregate concrete is 24.93 kN/mm², which are very close. This is in agreement with the results of Neville (1981) and Mosley and Bungey (1995). Furthermore, the standard deviation of the results obtained for original and washed recycled aggregate concretes are 0.26 N/mm² and 0.24 N/mm² respectively.

Table 4.23 Results of The Tensile Test of 9mm Diameter for Used Steel of Unknown Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	45	0	9	63.6	0	0.0000
20	45	0.7	9	63.6	314	0.0015
25	46.5	1.5	9	63.6	393	0.0333
30	48	3	9	63.6	472	0.0667
35	50	5	9	63.6	550	0.1111
37.5	55	10	8	50.3	746	0.2222

Gauge Length = 45mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	45	0	9	63.6	0	0.0000
20	45	0.7	9	63.6	314	0.0015
30	45	0.1	9	63.6	472	0.0022
35	45	0.12	9	63.6	550	0.0026
40	45	0.14	9	63.6	629	0.0030
45	48	3	9	63.6	708	0.0667
49.5	54	14	8	50.3	984	0.3111

Gauge Length = 45mm

Table 4.24 Results of The Tensile Test of 10mm Diameter for Used Steel of Known Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	50	0	10	78.5	0	0.0000
20	50	0.06	10	78.5	255	0.0012
30	50	0.09	10	78.5	382	0.0018
40	50	0.12	10	78.5	510	0.0025
50	51	1	10	78.5	637	0.020
60	53	3	10	78.5	764	0.060
65	57	7	9	63.6	1022	0.140

Gauge Length = 50mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	50	0	10	78.5	0	0.0000
20	50	0.07	10	78.5	255	0.0012
30	50	0.08	10	78.5	382	0.0018
40	51	1	10	78.5	510	0.0020
50	52	2	10	78.5	637	0.040
53	55	5	9	63.6	833	0.180

Gauge Length = 50mm

Table 4.25 Results of The Tensile Test of 11mm Diameter for Used Steel of Unknown Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	55	0	11	95	0	0.0000
10	55	0.03	11	95	105	0.0005
20	55	0.03	11	95	211	0.0007
30	55	0.08	11	95	316	0.0015
40	55	2	11	95	421	0.0020
50	57	2	11	95	526	0.036
60	60	5	11	95	632	0.091
64.5	63	8	10	78.5	822	0.145

Gauge Length = 55mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	55	0	11	95	0	0.0000
30	55	0.08	11	95	316	0.0015
40	59	4	11	95	421	0.0727
45	60	5	11	95	474	0.0909
50	61	6	11	95	526	0.1091
54	70	15	10	78.5	688	0.1818

Gauge Length = 55mm

Table 4.26 Results of The Tensile Test of 12mm Diameter Used Steel of Known Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	60	0	12	113	0	0.0000
30	60	0.07	12	113	265	0.0013
40	60	0.10	12	113	354	0.0017
50	60	0.13	12	113	442	0.0021
55	62	2	12	113	487	0.0333
60	62	2	12	113	531	0.0333
65	64	4	10	78.5	828	0.0667
67.5	67	7	10	78.5	860	0.1167

Gauge Length = 60mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	60	0	12	113	0	0.0000
40	60	0.11	12	113	354	0.0017
50	60	0.12	12	113	442	0.0021
60	61	1	12	113	531	0.0167
70	68	8	12	113	619	0.1333
75	74	14	11	95	789	0.2333
78	79	19	11	95	821	0.3167

Gauge Length = 60mm

Table 4.27 Results of The Tensile Test of 15mm Diameter Used Steel of Unknown Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	75	0	15	177	0	0.0000
60	75	0.12	15	177	339	0.0016
70	75	0.14	15	177	395	0.0019
80	75	0.17	15	177	452	0.0022
90	75	0.18	15	177	508	0.0024
100	75	0.20	15	177	565	0.0027
110	76	1	15	177	621	0.0133
120	78	3	14	154	779	0.4000
130	83	8	13	133	977	0.1067

Gauge Length = 75mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	75	0	15	177	0	0.0000
60	75	0.12	15	177	339	0.0016
70	77	2	15	177	395	0.0267
80	78	3	15	177	452	0.0400
90	80	5	14	154	584	0.0667
100	97	12	14	154	649	0.1600

Gauge Length = 75mm



Table 4.28 Results of The Tensile Test of 16mm Diameter Used Steel of Known Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	80	0	16	201	0	0.0000
60	80	0.11	16	201	299	0.0014
80	80	0.15	16	201	398	0.0019
100	80	0.19	16	201	498	0.0024
110	80	0.21	16	201	547	0.0026
120	81	1	16	201	597	0.0125
130	83	3	16	201	647	0.0375
140	86	6	14	154	909	0.0750

Gauge Length = 80mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	80	0	16	201	0	0.0000
60	80	0.12	16	201	299	0.0014
80	80	0.15	16	201	398	0.0019
100	80	0.19	16	201	498	0.0024
110	81	1	16	201	547	0.0125
120	82	2	16	201	597	0.0250
130	83	3	16	201	647	0.0375
138	85	5	15	177	780	0.0625

Gauge Length = 80mm

Table 4.29 Results of The Tensile Test of 19mm Diameter Used Steel of Unknown Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	95	0	19	284	0	0
60	95	0.10	19	184	211	0.0010
80	95	0.13	19	284	282	0.0014
100	97	2	19	284	352	0.0211
120	99	4	19	284	423	0.0421
140	105	10	18	254	551	0.1053
149	114	19	17	227	656	0.2000

Gauge Length = 95mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	95	0	19	284	0	0
80	95	0.13	19	284	282	0.0014
100	97	2	19	284	352	0.0211
120	99	4	19	284	423	0.0421
140	104	9	19	284	493	0.0950
160	107	12	18	254	630	0.1263
168	114	19	17	227	740	0.2000

Gauge Length = 95mm

Table 4.30 Results of The Tensile Test of 20mm Diameter Used Steel of Known Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	100	0	20	314	0	0.0000
80	100	0.12	20	314	255	0.0012
100	100	0.15	20	314	318	0.0015
120	100	0.18	20	314	382	0.0018
140	101	1	20	314	446	0.0100
160	103	3	20	314	510	0.0300
180	107	7	20	314	573	0.0700
197	114	14	19	284	694	0.1400

Gauge Length = 100mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	100	0	20	314	0	0.0000
80	100	0.12	20	314	255	0.0012
100	100	0.16	20	314	318	0.0016
120	100	0.17	20	314	382	0.0017
140	101	1	20	314	446	0.0100
160	103	3	20	314	510	0.0300
180	105	5	20	314	573	0.0500
200	110	10	19	284	704	0.1000
220	114	14	19	284	775	0.1400
222	119	19	18	254	874	0.1900

Gauge Length = 100mm

Table 4.31 Results of The Tensile Test of 24mm Diameter Used Steel of Unknown Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	120	0	24	452	0	0
160	120	0.20	24	452	354	0.0017
180	120	0.23	24	452	398	0.0019
200	120	0.24	24	452	442	0.0020
220	122	2	24	452	487	0.01667
240	123	3	24	452	531	0.0250
260	128	8	24	452	575	0.0667
280	130	10	24	452	619	0.0833
290	132	12	23	415	699	0.1000
297	135	15	23	415	716	0.1250

Gauge Length = 120mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	120	0	24	452	0	0
180	120	0.23	24	452	398	0.0019
200	120	0.25	24	452	442	0.0021
220	122	2	24	452	487	0.01667
240	123	3	24	452	531	0.025
260	123	3	23	415	627	0.0250
280	127	7	23	415	675	0.0583
300	129	9	22	380	789	0.0750
310	133	13	22	380	816	0.10833
314	144	24	21	346	908	0.2000

Gauge Length = 120mm

Table 4.32 Results of The Tensile Test of 25mm Diameter Used Steel of Known Origin.

(a)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	125	0	25	491	0.0	0.0
180	125	0.23	25	491	367	0.00180
200	125	0.25	25	491	407	0.00200
220	125	0.25	25	491	448	0.00220
240	125	0.30	25	491	489	0.00240
260	125	0.33	25	491	530	0.00260
280	126	1	25	491	570	0.00800
300	127	2	24.5	471	637	0.01600
320	130	5	24	452	708	0.04000
330	132	7	23.5	434	760	0.05600
333	134	9	23	415	802	0.07200

Gauge Length = 125mm

(b)

Load (kN)	Gauge length + Extension (mm)	Extension (mm)	Diameter (mm)	Area (mm ²)	Stress (σ) (N/mm ²)	Strain (ϵ)
0	125	0	25	491	0	0
180	125	0.22	25	491	367	0.0017
200	125	0.25	25	491	407	0.0020
220	126	1	25	491	448	0.0080
240	127	2	25	491	489	0.0160
260	128	3	24.5	471	530	0.0240
280	129	4	24	452	619	0.0320
300	130	5	23.5	434	691	0.0400
320	133	8	23	415	771	0.0640
330	135	10	23	415	795	0.0800
338	137	12	23	415	814	0.0960

Gauge Length = 125mm.

4.2.10 Modulus of elasticity (E_s) of steel

From the slope of the straight portion of stress-strain curves presented in Appendixes VIII – XI as obtained from Tables 4.23 - 4.32, the modulus of elasticity for used steel of known origin and used steel of unknown origin ranges from 202 to 208 kN/mm^2 , which is in agreement with values given by Gravessmith (1985), Benham and Grawford (1991) and BS 5950 (2000).

Table 4.33 Tensile Strength (N/mm²)

S/No.	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	14mm New Steel of Unknown Origin	14mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Unknown Origin	20mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	10mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	10mm Used Steel of Unknown Origin
1	640	688	506	695	697	697	541	592	682	697	616	734	673	677	469	616	631	675	558	590
2	688	692	511	690	685	707	521	570	662	682	554	740	602	673	469	674	631	822	558	778
3	682	697	509	697	675	729	546	595	657	687	565	689	673	655	469	689	631	726	582	763
4	625	682	511	657	666	666	529	606	687	677	559	712	673	664	469	610	631	675	553	597
5	640	688	542	679	697	736	516	567	627	682	562	616	655	681	469	695	618	669	583	763
6	668	688	515	701	682	729	556	577	677	686	548	746	673	690	469	705	618	675	550	755
7	682	715	520	544	685	713	556	556	662	706	542	678	633	672	473	674	611	726	557	621
8	648	676	520	675	675	682	570	567	657	701	627	734	624	650	469	679	624	662	566	770
9	605	676	515	695	627	697	549	581	647	677	520	576	628	646	473	568	631	662	553	739
10	621	678	489	657	608	704	567	592	662	677	576	734	677	659	473	747	618	656	582	763
11	678	676	507	653	704	742	528	554	647	731	554	746	673	690	473	695	631	656	558	583
12	688	697	520	723	685	748	525	556	677	701	548	627	664	673	473	674	624	675	542	778
13	686	703	513	726	694	678	539	585	682	697	554	633	637	690	469	684	631	662	574	582
14	688	680	515	657	656	756	532	563	657	726	571	644	664	655	476	716	631	682	580	739
15	672	682	507	726	710	720	546	563	687	697	559	571	664	673	469	674	631	650	550	770

Table 4.34 Yield Strength (N/mm²)

S.No.	15mm New Steel of Known Origin	25mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	25mm New Steel of Known Origin	25mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	10mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	10mm New Steel of Unknown Origin	10mm Used Steel of Unknown Origin
1	428	550	288	465	478	478	303	317	423	547	339	508	531	575	265	316	510	573	314	414
2	428	550	288	509	478	478	317	335	423	572	339	480	575	531	265	421	510	466	314	429
3	509	509	299	465	414	478	287	335	448	597	339	508	575	442	265	421	510	510	314	429
4	550	509	288	465	494	478	303	317	498	547	311	452	531	575	265	421	510	510	314	414
5	479	509	288	465	494	494	317	317	448	522	339	367	531	531	265	421	510	510	236	429
6	560	509	288	465	478	525	317	317	448	547	339	339	531	442	265	421	510	573	314	450
7	428	509	299	332	478	525	303	317	448	547	339	508	531	487	265	316	510	637	314	414
8	420	550	288	465	478	478	303	317	398	547	311	452	575	442	265	316	510	510	314	414
9	428	550	254	587	478	478	317	317	448	547	339	508	531	531	265	421	510	382	314	414
10	509	550	254	420	478	478	317	317	547	597	339	339	531	442	265	421	510	466	314	429
11	509	468	299	465	478	478	299	317	448	547	311	452	531	531	265	316	510	573	314	472
12	540	509	299	465	478	478	299	317	448	597	339	395	531	487	265	316	510	466	314	414
13	519	550	299	553	494	478	299	317	547	547	339	367	531	487	265	316	510	510	314	414
14	509	468	299	465	494	478	299	317	547	572	339	339	575	575	265	474	510	466	314	429
15	509	428	299	420	494	494	317	317	423	572	339	339	531	531	265	421	510	573	314	429

Table 4.35 Percentage (%) Elongation

Sl.No.	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	24mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Known Origin	19mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	18mm New Steel of Known Origin	18mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	9mm Used Steel of Unknown Origin	9mm New Steel of Unknown Origin
1	23.2	14.4	30.0	21.7	17.0	26.0	19.0	16.8	5.0	7.5	17.3	20.0	5.0	10.0	21.7	27.5	18.0	20.0	22.2	22.0
2	23.2	23.3	23.3	20.0	24.0	19.0	22.1	18.9	18.8	5.0	14.7	22.7	10.0	13.3	20.0	23.3	14.0	10.0	28.9	20.0
3	26.7	22.4	28.5	22.5	11.0	26.0	26.0	15.8	5.0	7.5	16.0	12.0	6.7	13.3	25.0	12.7	16.0	14.0	20.0	17.8
4	26.0	17.6	27.5	18.3	24.0	17.0	16.0	27.4	18.8	10.3	12.0	20.0	5.0	11.7	16.7	16.4	13.0	12.0	21.1	12.2
5	22.4	19.2	29.2	27.5	17.0	21.0	11.6	18.0	16.3	6.3	17.3	17.3	13.3	15.0	31.7	16.4	16.0	8.0	20.0	17.8
6	24.0	23.3	21.7	20.0	15.0	24.0	25.2	17.9	16.3	6.3	24.0	23.7	16.7	11.7	33.3	10.9	16.0	8.0	24.4	21.1
7	18.4	14.4	32.5	18.3	20.0	13.0	21.0	15.8	5.0	10.0	17.3	5.3	16.7	10.0	23.3	14.5	13.0	10.0	22.2	14.4
8	24.0	17.6	33.3	20.8	24.0	18.0	22.1	21.1	18.8	7.5	26.7	22.7	10.0	8.3	21.7	18.2	15.0	8.0	24.4	20.0
9	13.8	13.8	26.7	29.2	16.0	23.0	23.2	25.3	8.8	6.3	22.7	17.3	19.2	16.7	21.7	16.4	18.0	8.0	26.7	24.4
10	17.6	10.4	23.3	16.2	26.0	23.0	29.2	18.9	20.0	11.3	22.7	9.3	10.0	10.0	26.7	23.6	14.0	10.0	20.0	15.6
11	11.2	19.2	23.3	20.0	21.0	13.0	23.2	16.0	21.3	10.0	20.0	16.0	13.3	6.7	20.0	23.6	18.0	10.0	15.6	20.0
12	19.2	16.8	20.8	19.2	25.0	28.0	24.2	22.1	7.5	7.5	25.3	17.3	15.0	11.3	18.3	14.5	18.0	10.0	20.0	20.0
13	18.4	21.6	29.2	18.3	22.0	16.0	28.4	28.4	6.3	16.3	22.7	20.0	13.3	18.3	25.0	27.3	12.0	8.0	24.4	26.7
14	23.2	17.6	36.7	25.0	9.0	24.0	28.4	16.8	15.0	6.3	17.3	25.3	11.7	5.0	25.0	14.3	14.0	10.0	22.2	20.0
14	14.4	12.0	27.5	21.2	21.0	19.0	25.0	24.2	7.5	6.3	32.7	22.7	10.0	16.7	25.0	18.2	16.0	18.0	22.2	20.0

Table 4.36 Percentage (%) Reduction in Area

S/No.	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	20mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Known Origin	19mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	16mm New Steel of Known Origin	16mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	9mm Used Steel of Unknown Origin	9mm New Steel of Unknown Origin
1	29.4	48.2	55.5	23.4	51.0	36.0	36.0	29.2	43.7	52.7	13.0	55.6	43.7	15.9	65.9	30.0	51.0	36.0	55.3	55.0
2	39.0	36.0	49.8	37.3	51.0	36.0	37.8	29.2	34.0	42.7	64.1	64.1	30.5	55.5	65.9	42.1	43.7	51.0	55.3	30.5
3	48.2	42.3	43.7	43.7	27.7	43.7	43.7	17.8	52.7	52.7	55.6	64.1	30.5	15.9	65.9	12.3	51.0	51.0	39.5	39.5
4	48.2	36.0	49.8	43.7	27.7	36.0	27.7	37.8	43.7	42.7	55.6	64.1	55.5	30.5	65.9	12.3	36.0	36.0	39.5	55.6
5	42.2	42.3	43.7	43.7	43.7	36.0	29.2	29.2	43.7	42.7	13.0	20.0	55.5	55.5	65.9	12.3	36.0	19.0	39.5	39.5
6	31.0	42.3	43.7	23.4	43.7	36.0	37.8	29.2	43.7	74.0	55.6	42.7	55.5	15.9	70.0	12.3	36.0	36.0	39.5	49.1
7	42.2	36.0	23.4	15.9	22.7	43.7	36.0	29.2	52.7	61.0	13.0	55.6	43.0	15.9	65.9	59.5	43.7	36.0	55.3	39.5
8	29.4	48.2	43.7	37.3	19.0	27.7	36.0	37.8	52.7	34.0	55.6	36.1	43.7	30.5	65.9	12.3	51.0	27.7	21.0	49.1
9	42.2	48.2	23.4	37.3	51.0	27.7	37.8	37.8	23.4	52.7	55.6	64.1	30.5	15.9	65.9	59.5	36.0	19.0	21.0	30.5
10	53.8	36.0	52.7	23.4	19.0	43.7	29.2	29.2	43.7	42.7	46.4	36.1	43.7	43.7	65.9	59.5	51.0	19.0	39.5	21.0
11	42.2	42.3	30.5	23.4	43.7	43.7	37.8	21.1	52.7	52.7	55.6	55.6	55.5	30.5	65.9	47.1	36.0	36.0	21.0	39.5
12	48.2	48.2	49.8	23.4	27.7	27.7	29.0	37.8	43.7	42.7	46.4	36.1	55.5	15.9	65.9	47.1	36.0	19.0	39.5	55.6
13	36.0	36.0	49.8	43.7	36.0	27.7	36.0	37.8	34.0	34.0	4.4	55.6	30.5	30.5	65.9	59.5	36.0	51.0	39.5	21.0
14	48.2	42.3	49.8	43.7	19.0	43.7	37.8	29.2	43.7	42.7	46.4	46.3	30.5	30.5	65.9	17.3	51.0	36.0	39.5	21.0
15	42.2	48.2	49.8	43.7	27.7	36.0	43.7	37.8	43.7	23.4	55.6	46.3	30.5	15.9	65.9	47.1	36.0	36.0	21.0	21.0

4.2.11 Used steel

Results emanating from this study show that the tensile strength of used steel of known origin ranges from 531.13 N/mm^2 to 661.48 N/mm^2 while from the work by Raji (2005), the tensile strength of new steel of known origin ranges from 594.69 N/mm^2 to 611.23 N/mm^2 . From the results of this work, the tensile strength of used steel of unknown origin ranges from 465.21 N/mm^2 to 573.83 N/mm^2 while from the work by Daodu (2005), the tensile strength of new steel of unknown origin ranges from 465.21 N/mm^2 to 559.0 N/mm^2 . The yield strength of used steel of known origin from the results of this work ranges from 350.0 N/mm^2 to 510.0 N/mm^2 while from the work by Raji (2005), the yield strength of new steel of known origin ranges from 350.70 N/mm^2 to 507.0 N/mm^2 . The yield strength of used steel of unknown origin from the results of this work ranges from 253.63 N/mm^2 to 330.26 N/mm^2 while from the work by Daodu (2005), the yield strength of new steel of unknown origin ranges from 253.63 N/mm^2 to 306.4 N/mm^2 . The results of this study show that the tensile strength of used steel of known origin and used steel of unknown origin is 5% to 22% higher than the tensile strength of the corresponding new steel of known origin and new steel of unknown origin presented in the works by Raji (2005) and Daodu (2005). In addition to this, the yield strength of used steel of known origin and used steel of unknown origin is 4% to 48% higher than the yield strength of the corresponding new steel of known origin and new steel of unknown origin as presented by Raji (2005) and Daodu (2005). On the other hand, the results showed that the ductility constants of used steel of known origin and used steel of unknown origin is lower than the ductility constants of the corresponding new steel of known origin and new steel of unknown origin with a reduction of about 13% for percentage elongation and 15% for percentage reduction in area. Furthermore,

from the results of this work and the work by Raji (2005), the values of percentage elongation of used steel of known origin and new steel of known origin are less than 14% as specified by international standard. This shows clearly that used steel of known origin and new steel of known origin are brittle materials. The values of percentage elongation of used steel of unknown origin from the results of this work and new steel of unknown origin from the work by Daodu (2005) are in the neighbourhood of 16% which is the standard value for mild steel (ductile material) specified by international standard.

The increase in strength and reduction in ductility constants could be attributed to the fact that the materials have been subjected to load recycle which has resulted to stretching and strain hardening. When new reinforcing steel in a concrete structure is subjected to a form of loading, it is strained - the amount of such strain or distortion depends on the severity of the force producing it. When this reinforcing steel specimen is removed from waste structural concrete now known as used steel is tested in a tensile testing machine, load will be applied and the steel will be subjected to another tensile stress. This series of loading is known as loading recycling which is synonymous to cold working being carried out on the steel when it is cold. The effect of this directional working, that is, stretching and case hardening is to elongate the grain structure of the material in the direction of the strain or distortion. The general effect of this is to increase the hardness and tensile strength, to reduce ductility and to make metal more brittle (Chapman, 1975).

It is evidently clear from the results of this study that used steel of known origin and new steel of known origin conform to international standard in terms of strengths (tensile and yield), ductility constants and systems of marking while used steel of unknown origin and new steel of unknown origin does not conform to international

standard in terms of strength (tensile and yield), ductility constants and systems of marking, but instead, it showed tensile strength and yield strength similar to mild steel bars. This is further illustrated in the stress-strain graphs shown in Appendixes VIII-XI. For the reasons stated above, it is evident that used steel of unknown origin and new steel of unknown origin are ribbed mild steel while used steel of known origin and new steel of known origin are ribbed high yield steel. Lastly, the results of this study has established that because of cost and deception, manufacturers of new steel of unknown origin and used steel of unknown origin produce ribbed mild steel bars and sell it as ribbed high yield steel bars.

Table 4.37 Statistical Analysis

1. Tensile Strength (N/mm²)

	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	24mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	28mm New Steel of Known Origin	20mm Used Steel of Known Origin	18mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	16mm New Steel of Known Origin	16mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	9mm Used Steel of Unknown Origin	9mm New Steel of Unknown Origin
Standard Deviation (N/mm ²)	28.35	11.34	11.08	44.85	27.97	24.93	16.38	16.22	17.25	16.73	26.93	62.82	23.37	14.66	2.49	44.70	6.81	15.71	13.71	62.79
Mean (X) (N/mm ²)	666.7	687.90	513.3	678.33	676.40	712.27	541.4	574.93	664.67	694.9	563.57	678.67	654.20	669.87	470.80	673.33	626.13	563.07	563.07	506.03
Required Characteristic Value (f _d) (N/mm ²)	594.99 > 500	661.48 > 500	487.48 > 430	572.83 > 430	611.23 > 500	654.18 > 500	503.23 > 430	537.14 > 430	624.57 > 500	655.95 > 500	500.92 > 430	552.30 > 430	599.75 > 500	635.85 > 500	465.21 > 430	569.18 > 430	610.26 > 500	531.13 > 500	531.13 > 430	559.77 > 430

2. Yield Strength (N/mm²)

	25mm New Steel of Known Origin	23mm Used Steel of Known Origin	24mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Known Origin	19mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	18mm New Steel of Known Origin	18mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	8mm Used Steel of Unknown Origin	8mm New Steel of Unknown Origin
Standard Deviation (N/mm ²)	40.28	37.37	15.01	19.01	19.56	16.47	9.69	6.33	48.54	22.89	11.59	45.68	30.14	49.89	8	37.80	6	28.02	20.14	16.17
Mean (X) (N/mm ²)	488.33	514.53	288.60	467.73	479.07	487.07	108.47	319.4	462.80	580.33	571.40	423.53	542.73	507.37	265.00	382.53	510.0	509.67	308.80	426.27
Required Characteristic Value (f _y) (N/mm ²)	373.51 > 350	427.46 > 350	253.63 > 250	330.26 > 250	433.50 > 350	448.70 > 350	283.89 > 250	304.65 > 250	349.70 > 350	507.00 > 350	306.4 > 250	318.88 > 250	495.80 > 350	301.03 > 350	265.00 > 250	294.46 > 250	510.0 > 350	444.42 > 350	261.87 > 250	388.13 > 250

3. Percentage (%) Elongation

	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	24mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Known Origin	19mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	16mm New Steel of Known Origin	16mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	9mm Used Steel of Unknown Origin	9mm New Steel of Unknown Origin
Standard Deviation %	4.65	4.03	4.54	3.55	3.15	4.70	4.72	4.27	6.31	2.87	5.37	6.97	4.24	3.74	4.55	5.58	2.03	3.69	3.20	3.6
Mean (X) %	20.33	17.55	27.35	21.28	19.47	20.67	23.84	20.29	12.69	8.03	20.58	18.94	11.73	12.00	23.67	18.79	15.40	10.93	22.20	19
Required Characteristic Value % (f_c)	9.50 < 14	8.16 < 14	16.97 < 16	11.06 < 16	7.47 < 14	9.72 < 14	11.84 < 16	10.34 < 16	2.01 < 14	1.34 < 14	8.07 < 16	2.60 < 16	1.85 < 14	1.17 < 14	13.07 < 16	5.79 < 16	10.67 < 14	2.33 < 14	15.83 < 16	10

4. Percentage (%) Reduction in Area

	25mm New Steel of Known Origin	25mm Used Steel of Known Origin	24mm New Steel of Unknown Origin	24mm Used Steel of Unknown Origin	20mm New Steel of Known Origin	20mm Used Steel of Known Origin	19mm New Steel of Unknown Origin	19mm Used Steel of Unknown Origin	18mm New Steel of Known Origin	18mm Used Steel of Known Origin	15mm New Steel of Unknown Origin	15mm Used Steel of Unknown Origin	12mm New Steel of Known Origin	12mm Used Steel of Known Origin	11mm New Steel of Unknown Origin	11mm Used Steel of Unknown Origin	10mm New Steel of Known Origin	10mm Used Steel of Known Origin	9mm New Steel of Unknown Origin	9mm Used Steel of Unknown Origin
Standard Deviation %	1.22	5.16	10.35	10.30	12.03	6.38	4.94	5.36	8.12	9.72	17.38	13.30	11.10	14.18	1.21	18.51	7.08	11.45	12.22	17.00
Mean (X) %	41.56	42.17	43.94	33.80	34.37	36.35	35.71	32.67	43.45	43.56	45.19	49.49	42.5	23.90	66.23	37.35	42.03	33.91	37.77	40.53
Required Characteristic Value % (f_d)	24.74	30.15	20.29	9.80	6.34	21.48	24.20	20.18	24.55	20.91	4.69	18.50	16.84	5.14	63.39	5.82	25.58	7.25	9.30	0.92

4.2.12 Statistical analysis

From the results, the high standard deviation for the strength and ductility constant was due to the fact that steel specimen, that is, used steel of known origin and used steel of unknown origin, were taken from different places and this shows wide variation in the properties obtained for each test piece from each supplier though all the results satisfied the minimum strength and ductility requirements as specified by the relevant codes.

Table 4.38 Cost Analysis of Original and Recycled Aggregate Concrete (per cubic meter)

Type of Concrete	Cost in Naira per cubic meter
Original Aggregate Concrete	13,868.00
Recycled Aggregate Concrete	11,035.00

Table 4.39 Cost Analysis of New Steel of both Known and Unknown Origin (per ton)

Steel Type	Cost in Naira per ton
Steel of Known Origin	220,000.00
Steel of Unknown Origin	195,000.00

Table 4.40 Cost Analysis of Used Steel of both Known and Unknown Origin (per ton)

Bar Size	Cost in Naira per ton
10mm	184,659.13
12mm	182,995.48
16mm	133,787.16
20mm	105,433.90
25mm	84,328.08

4.2.13 Cost comparison of recycled and normal structural concrete

It is evidently clear from the results of the cost analysis shown in Tables 4.38 – 4.40 that the cost of washed recycled aggregate concrete of granite composition is 20.4% less than original aggregate concrete of the same composition in Ogun State. In addition to this, the cost of used steel of known and unknown origin is between 10.5% and 58.5% less than the cost of new steel of known and unknown origin. The high price of 10mm and 12mm diameters used steel is as a result of high demand for these two sizes.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the results of this study, the following conclusions are hereby drawn:

- The cement paste on the recycled aggregate can be effectively removed by using a pair of wire brushes after the recycled aggregates has been soaked for about 14 days.
- At the same water-cement ratios, the workability of original aggregate concrete is higher than that of unwashed recycled aggregate concrete but similar to that of washed recycled aggregate concrete.
- It is the cement paste on the recycled aggregate that lowers the specific gravity, density and compressive strength of recycled aggregate concrete. This was evidenced by the fact that concrete produced with properly washed recycled aggregate showed similarity in specific gravity, aggregate crushing value and compressive strength compared to original aggregate concrete.
- Water absorption capacity of washed recycled aggregate concrete is similar to that of original aggregate concrete.
- At the same water-cement ratio, the modulus of elasticity of washed recycled aggregate concrete is similar to that of original concrete.
- At the same water-cement ratio, the bending strength of washed recycled aggregate concrete is similar to that of original aggregate concrete.

- The cost of recycled aggregate concrete is relatively less than that of the corresponding original aggregate concrete of granite composition
- The cement paste and other impurities on the used steel can be effectively removed by using wire brush.
- The cost of used steel of both known and unknown origin is relatively less than that of the corresponding of new steel of both known and unknown origin.
- The strengths of used steel of known origin are higher than those of the corresponding new steel and both satisfied the minimum strength requirements as specify by the relevant codes.
- The ductility constants of the used steel of known origin are slightly lower than those of corresponding new steel although both satisfied the minimum ductility requirements as specify by the relevant codes, and finally,
- Some ribbed bars in the market are indeed mild steel bars as experimentally evidenced by their strength and ductility characteristics of both new and used steel of unknown origin.

5.2 Recommendations

The following recommendations are hereby made:

- Research should be encouraged in the area of designing and constructing mechanically or electrically-powered crushing and sieving machines for the purpose of obtaining recycled aggregate for concrete in industrial quantities.
- Washed recycled aggregate could be employed for normal concrete work and is cheaper.
- Used steel of both known and unknown origin if appropriately cleaned could be used in normal concrete works because of the reduced cost. However such use should be limited to members and structures where ductile behaviour is not a primary requirement, and, finally,
- Steel of unknown origin should be considered as ribbed mild steel bars when designing members and structures.

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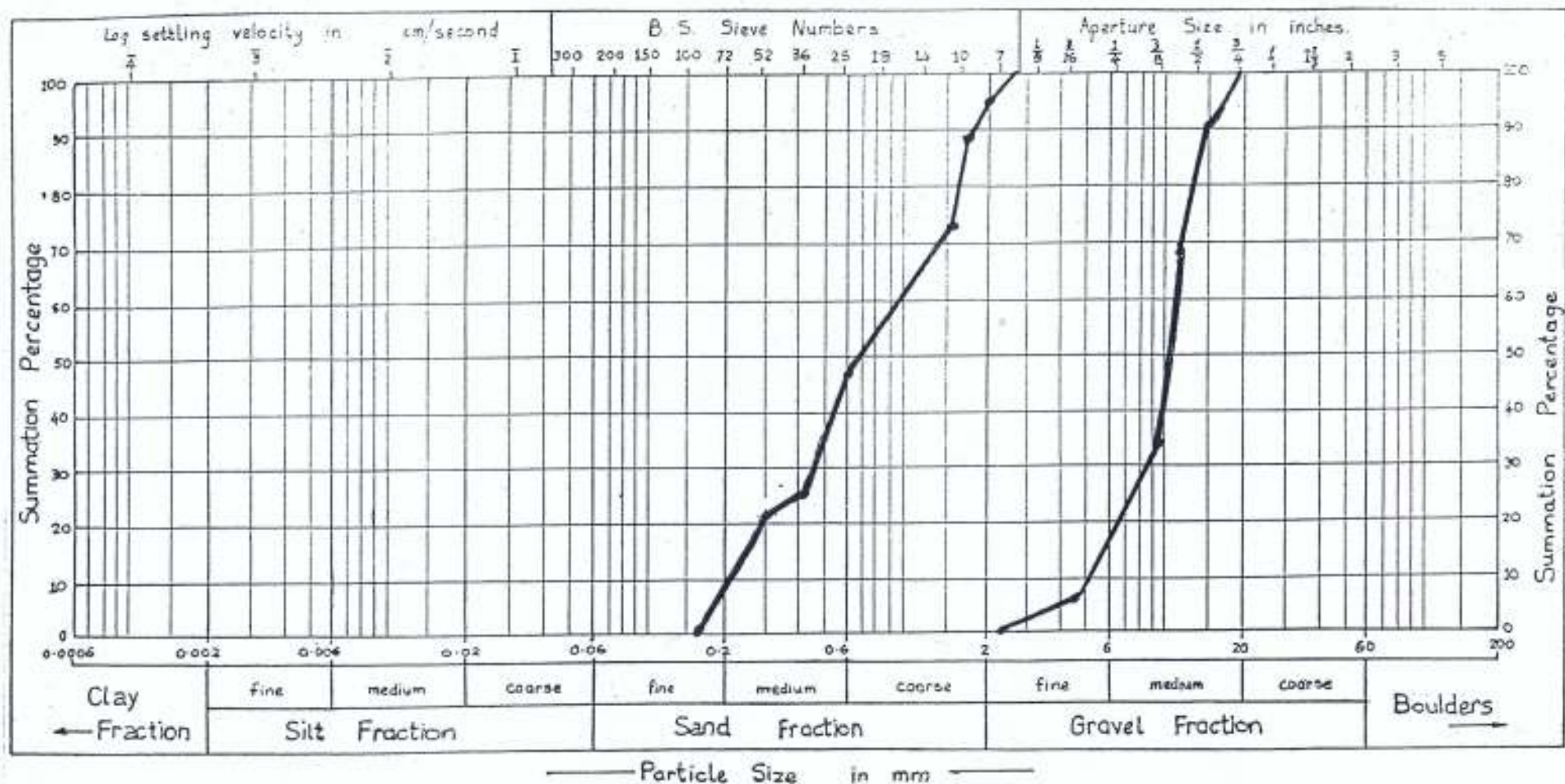
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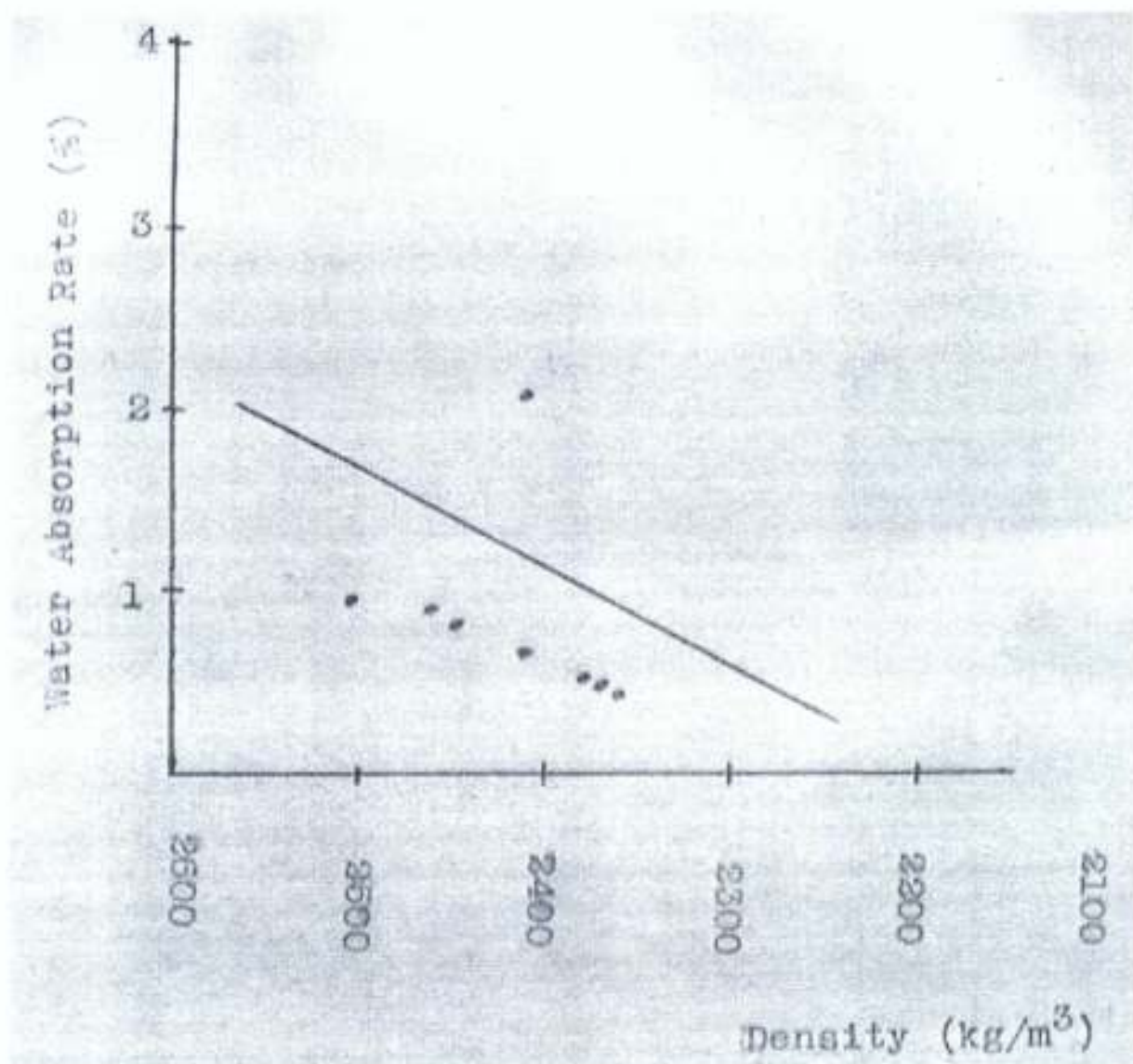
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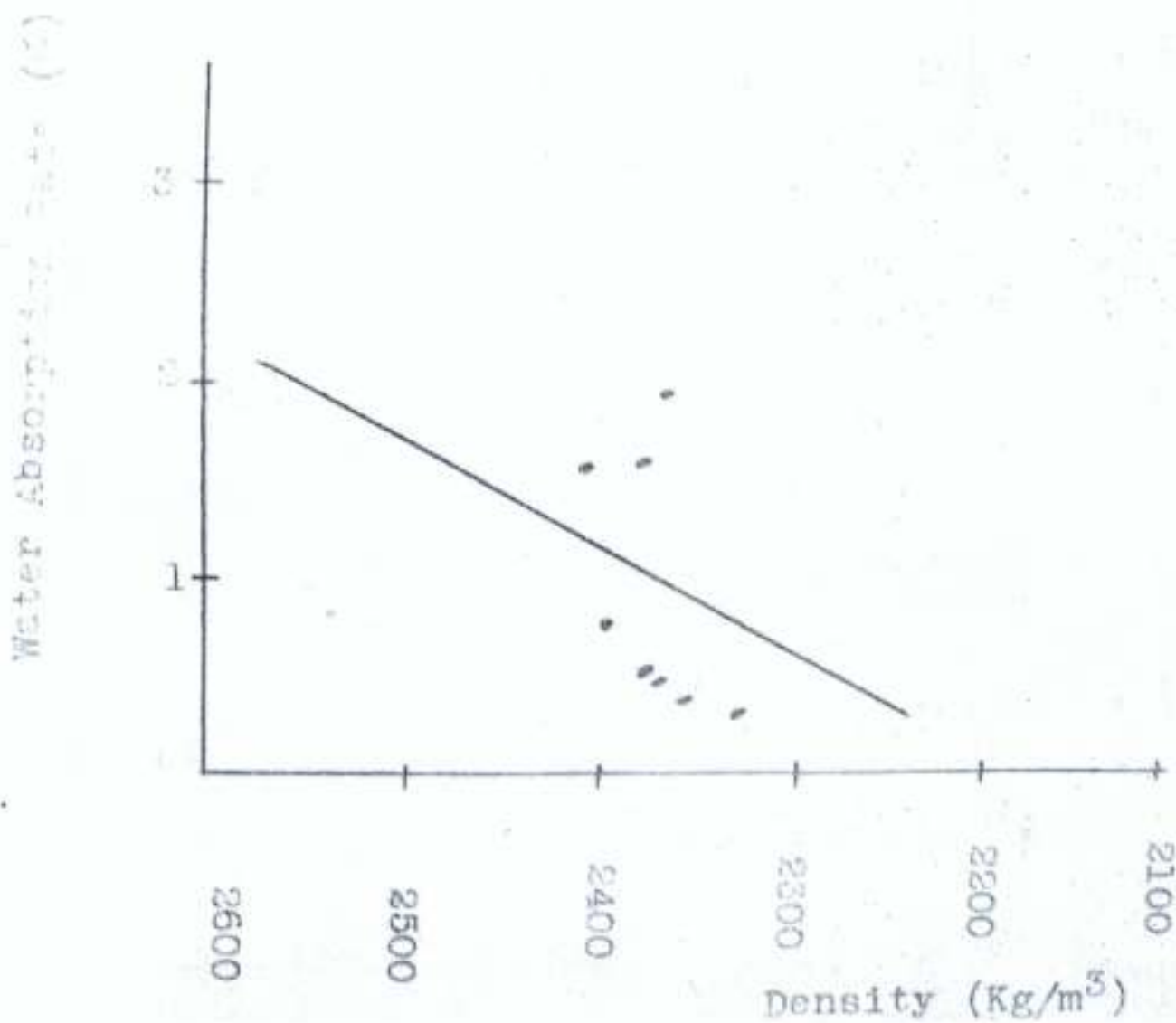
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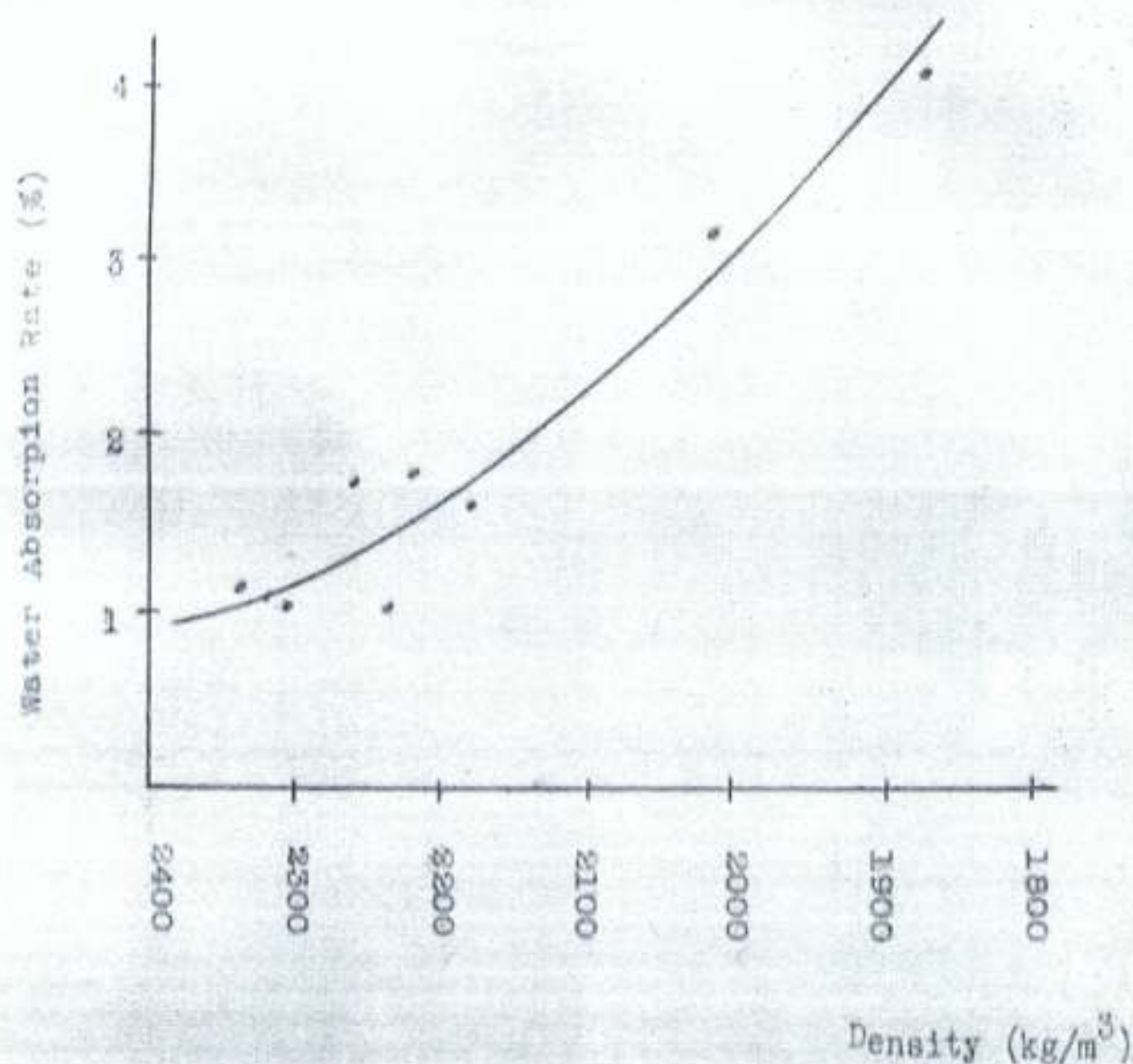
Appendix 1 Grading curves for original and recycled aggregates



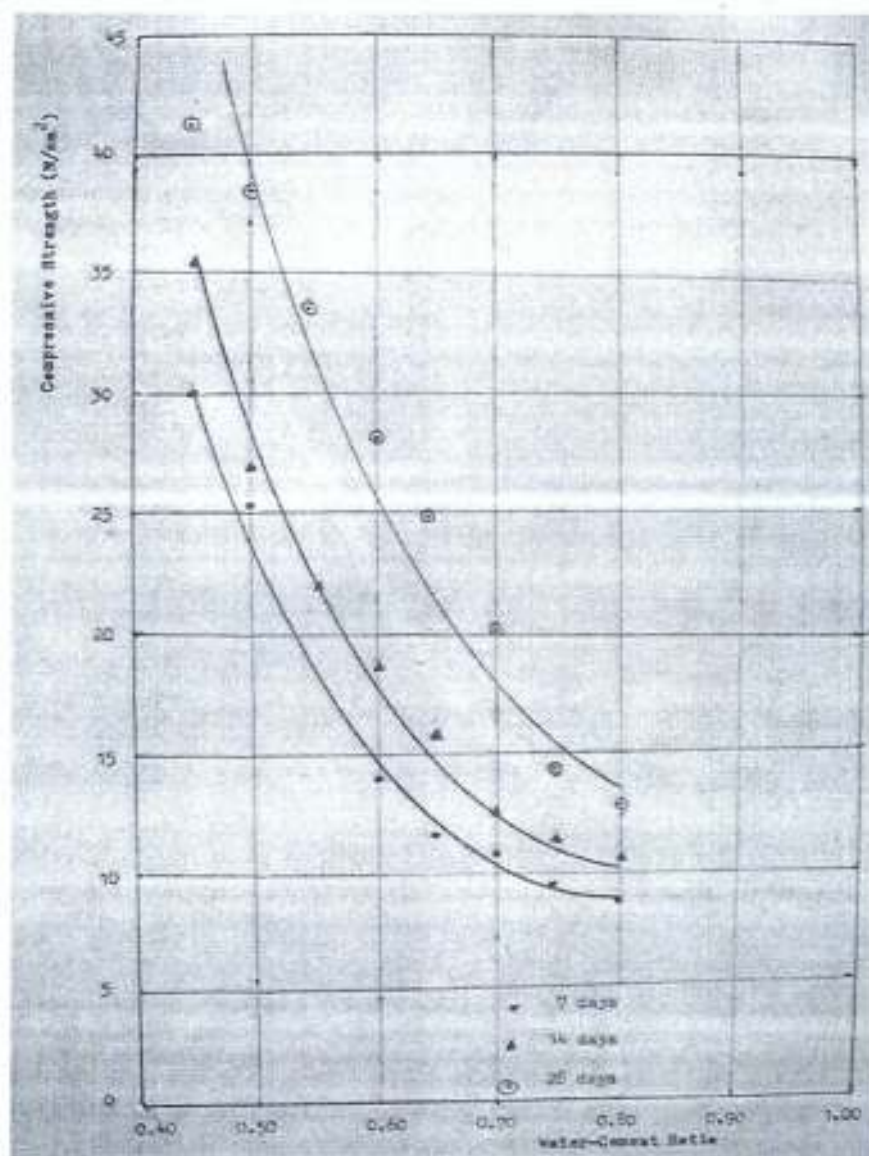
Appendix II: Water absorption rate in percent against density of original aggregate concrete.



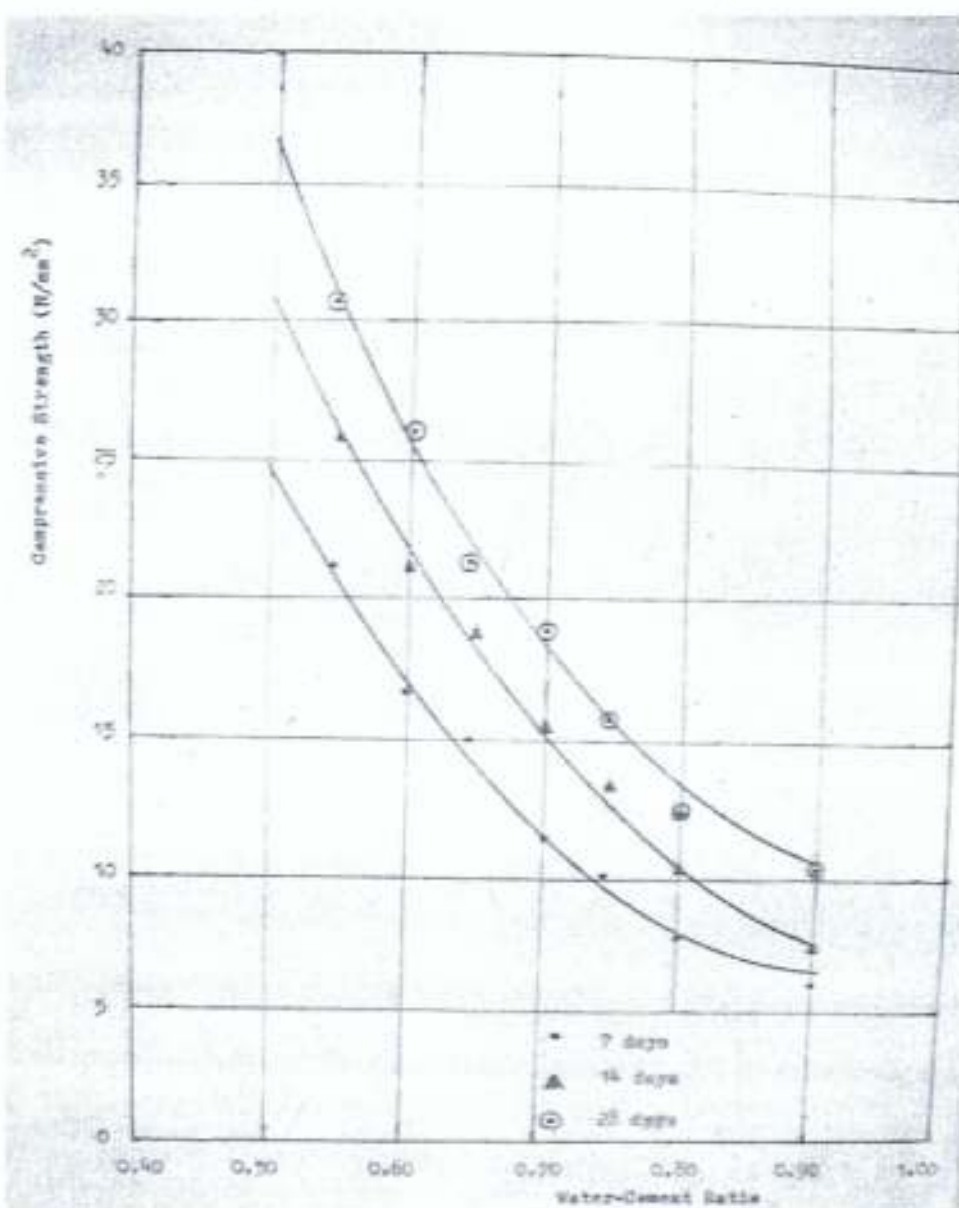
Appendix III: Water absorption rate in percent against density of washed recycled aggregate concrete.



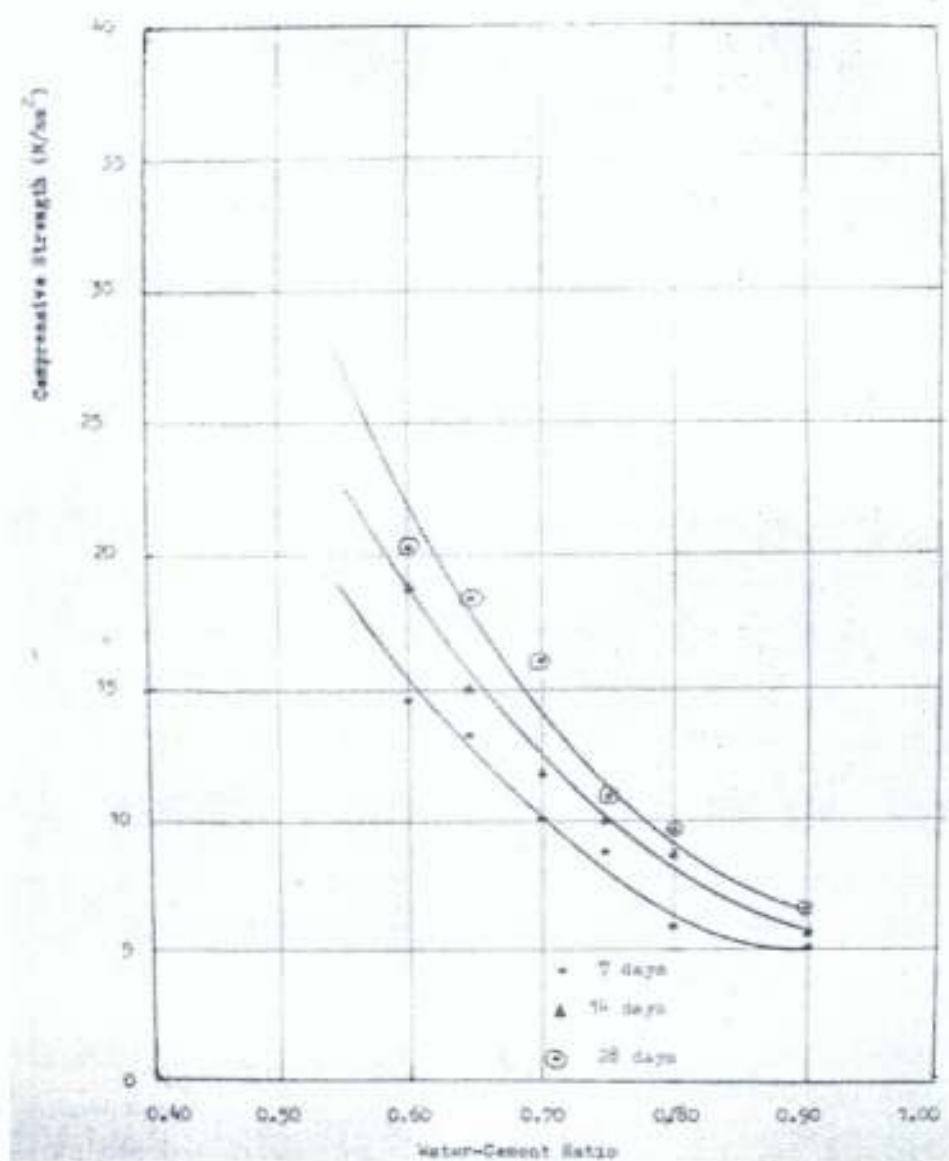
Appendix IV: Water absorption in percent against density of unwashed recycled aggregate concrete



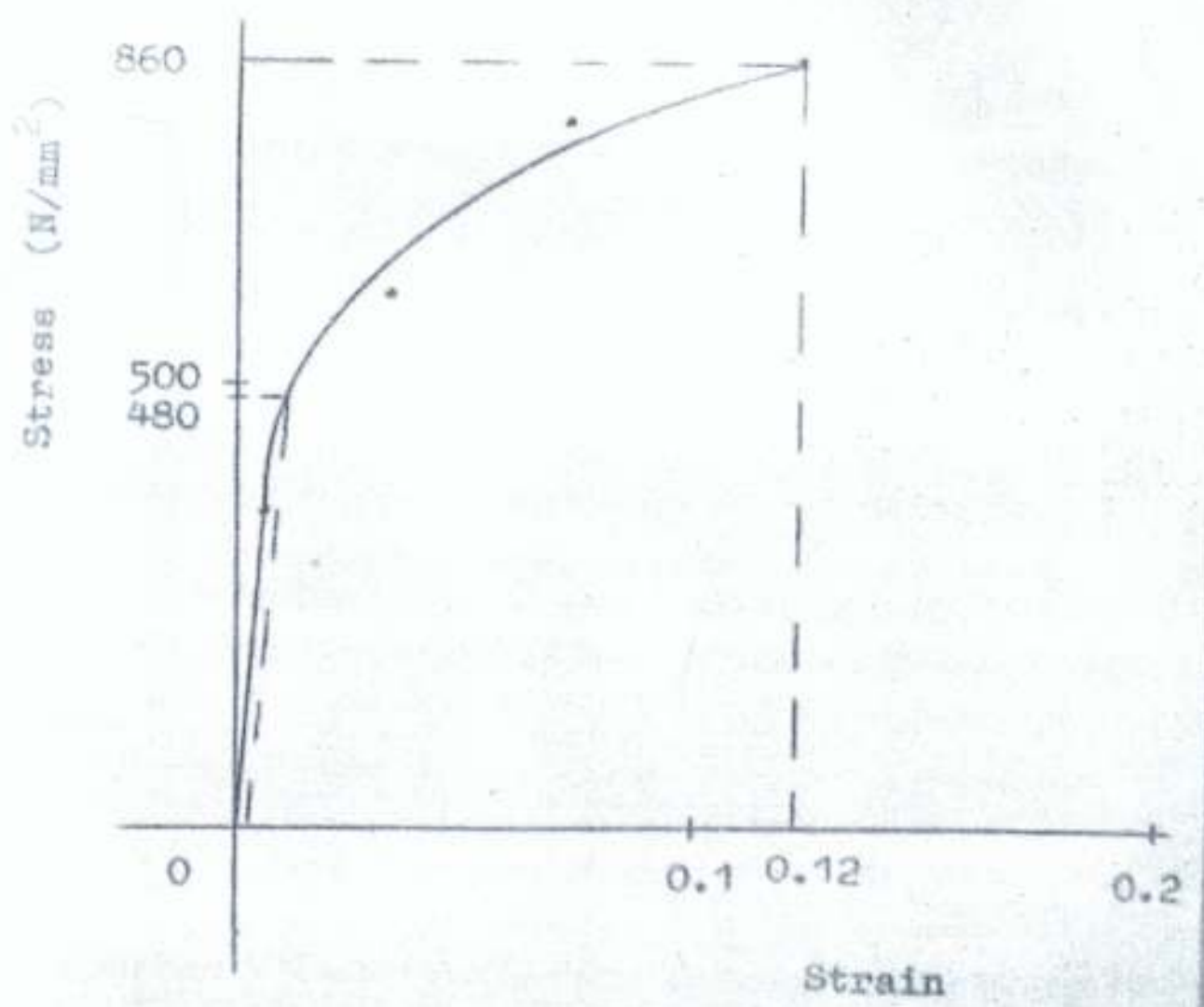
Appendix V: Compressive strength of original aggregate concrete against water-cement ratio.



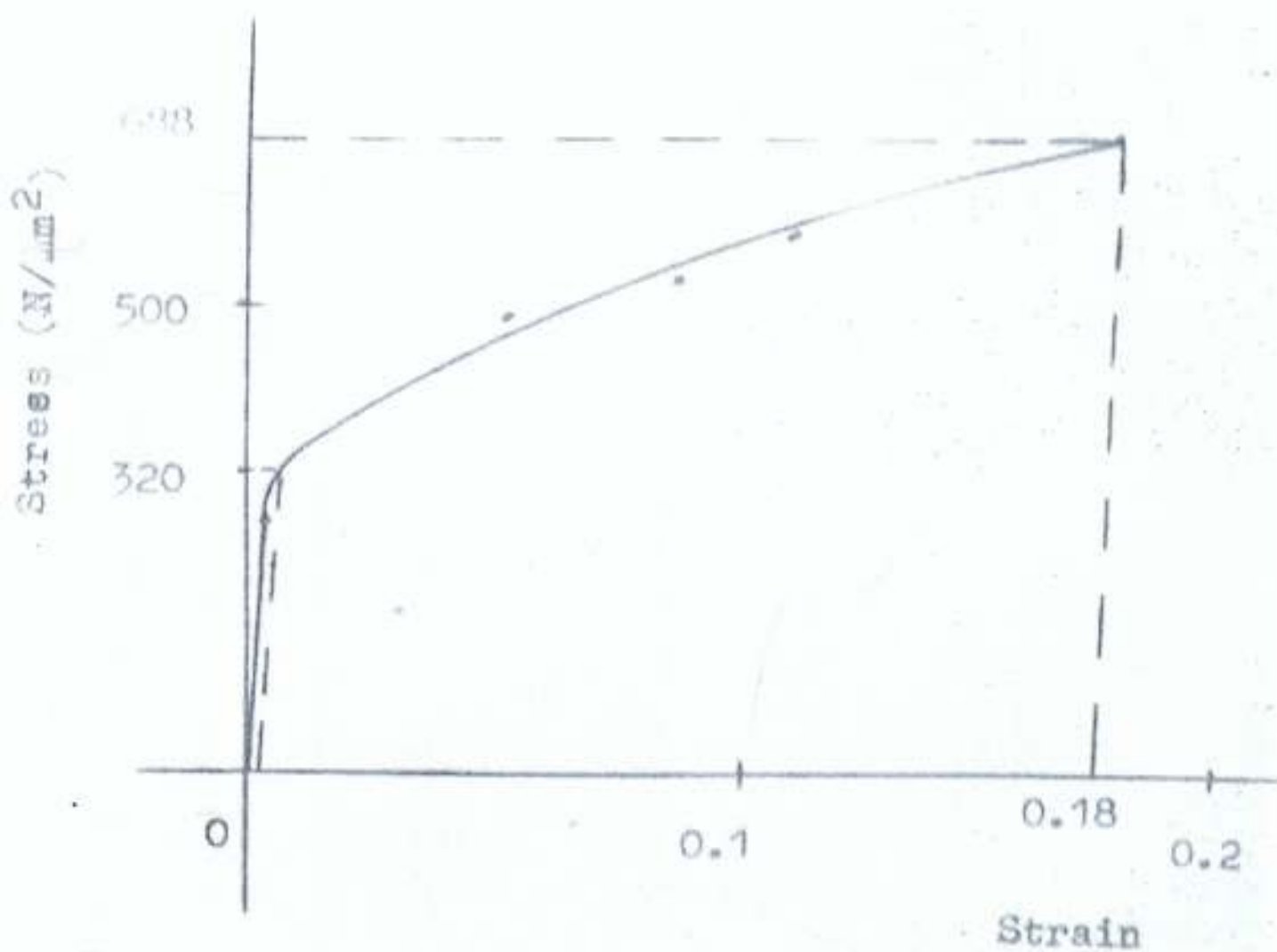
Appendix VI: Compressive strength of washed recycled aggregate concrete against water-cement ratio.



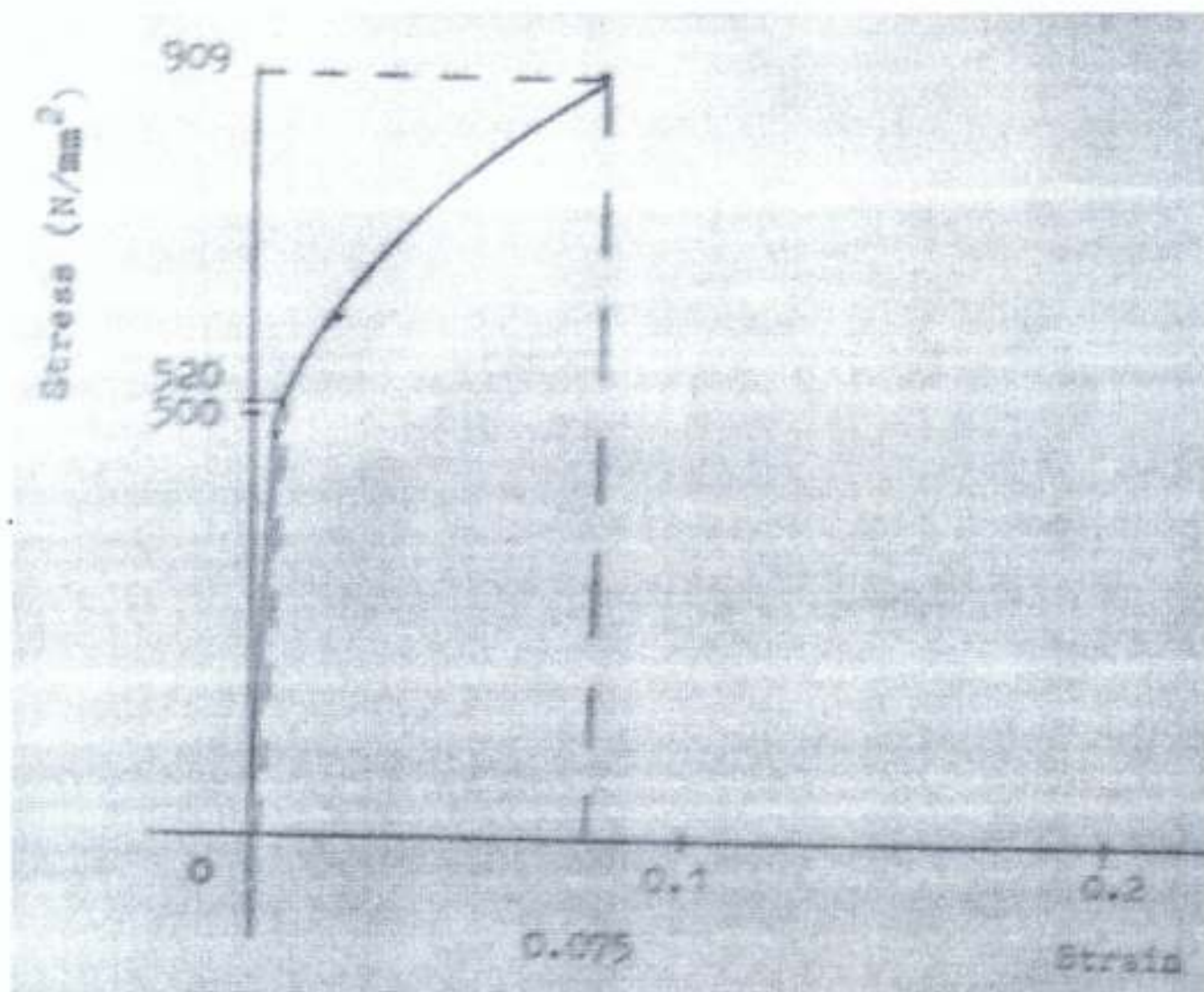
Appendix VII: Compressive strength of unwashed recycled aggregate against water-cement ratio.



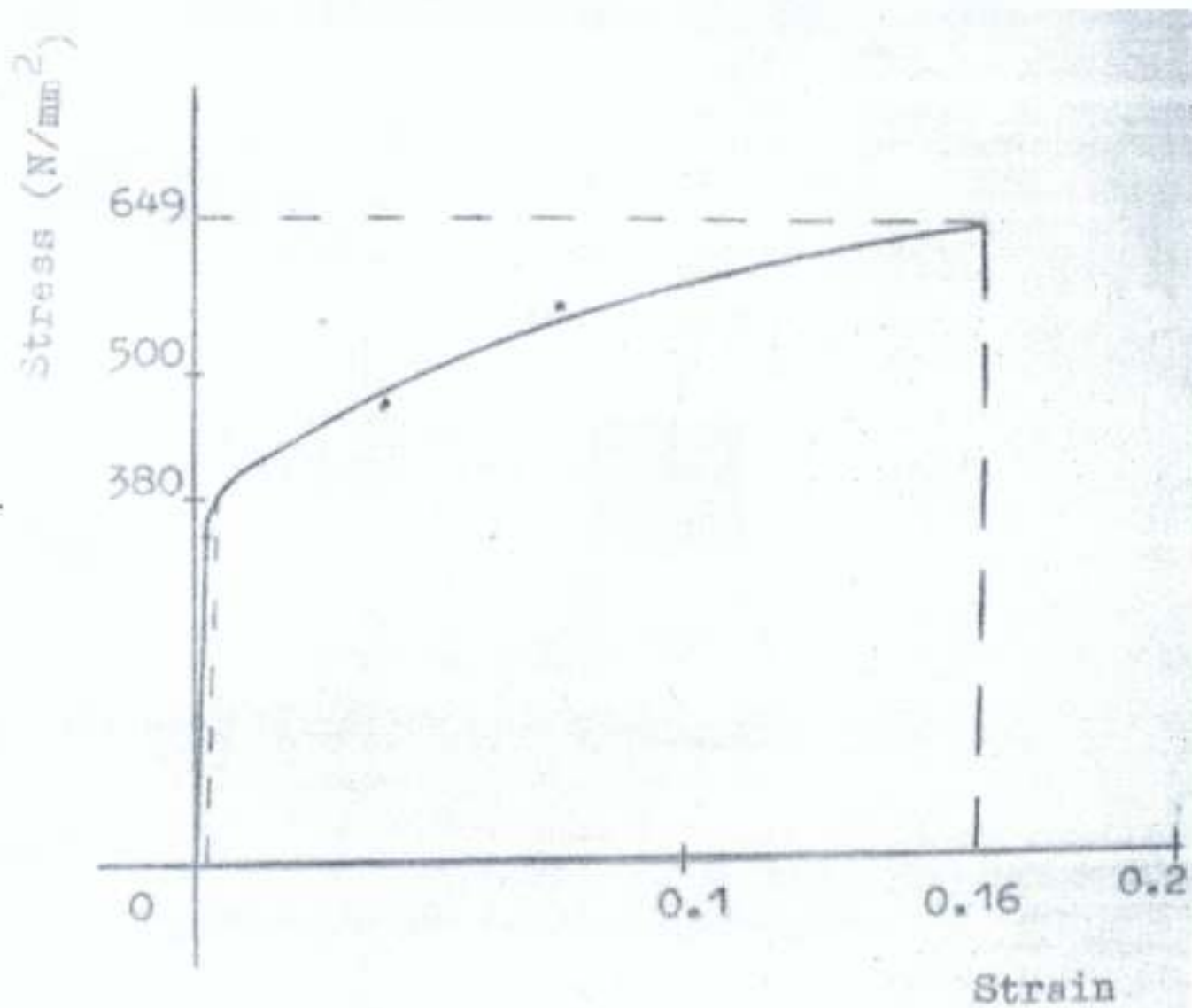
Appendix VIII: Stress-strain curve of 12mm diameter used steel of known origin.



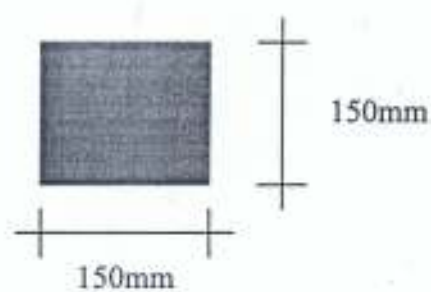
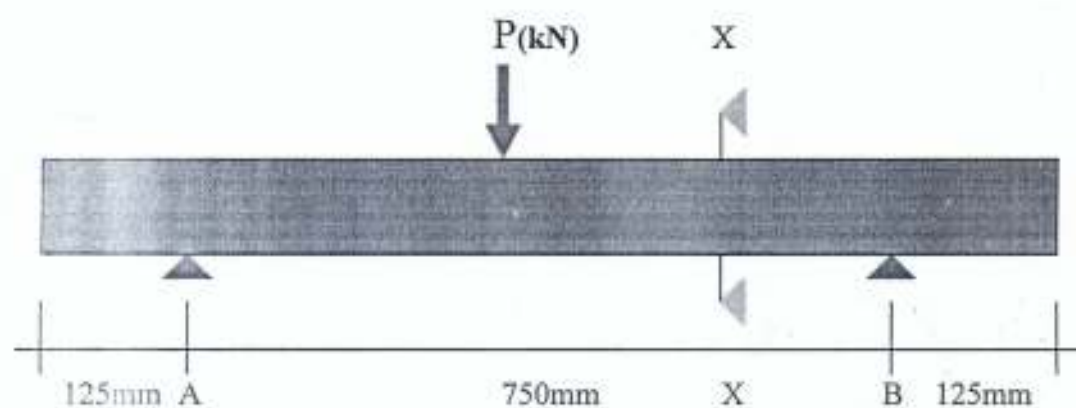
Appendix IX: Stress-strain curve of 11mm diameter used steel of unknown origin.



Appendix X: Stress-strain curve of 16mm diameter used steel of known origin.



Appendix XI: Stress-strain curve of 15mm diameter used steel of unknown origin.



Section X-X

Appendix XII: Schematic Diagram of Bending Strength Test