AN INVESTIGATION INTO THE, STRENGTH OF GAP-GRADED RECYCLED CONCRETE

BY

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D E C L A R A T I O N

I, Hussaini Patrick Mosisiyenemo declare that this thesis is solely the record of my work and has not been presented anywhere for any degree.

All sources of information have been duly acknowledged in the list of References and Bibliography.

Hussaini Patrick Mosisiyenemo

DECEMBER, 1991

Date

D E D I C A T I O N

This thesis is dedicated to the men who have had the greatest influence on my life.

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C E R T I F I C A T I O N

This thesis entitled "AN INVESTIGATION INTO THE STRENGTH OF GAP-GRADED RECYCLED CONCRETE" by Hussaini Patrick Mosisiyenemo meets the regulations governing the award of the degree of Master of Science (in Construction Technology) of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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ABSTRACT

This thesis presents the results of experimental studies on the effect(s) of Gap-grading on the strength of Recycled concrete.

Five concrete mixtures were made of gap-graded and continuously graded mixes in the strength range of 12.9N/mm^2 to 21.9N/mm^2 with 20 mm maximum size coarse aggregates, and fine sand. The water-cement and aggregate-cement ratios by weight of the mixes were kept constant at 0.7 and 9.0 respectively. The fine aggregate (riverbed sand) content varied from 20 to 50 percent, with Zaria crushed granite and crushed concrete used as coarse aggregates. Three gaps with intermediate size groups between 10 mm and 1.18 mm sizes missing were introduced. The experimental programme included tests on determination of some aggregate properties, workability, compressive and tensile strength of concrete specimens. The range of variation in concrete strength due to aggregate grading alone was as high as 25 percent, compressive strength being affected more than the tensile strength.

Within the premise of this study, the results indicate that:

(a) All other things being equal gap-graded recycled concrete may be superior to continuously graded recycled concrete in terms of compressive and tensile strength.

(b) The characteristicaly lower strength of concrete mixtures that contain recycled concrete may be increased by the introduction of gaps in the grading of a mixture that contains recycled concrete

(c) 25 percent sand content should be the minimum value allowed in the mixtures of gap-graded recycled concrete.

(d) Gap-graded recycled concrete, though of a relatively stiffer and drier mix, can be placed and finished satisfactorily using mechanical vibrators to ensure that full compaction is achieved.
It may therefore be used to advantage to conserve supplies of natural aggregates and to eliminate it as a problem of solid waste disposal.

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Chapter 1.

INTRODUCTION

1.1 General Introduction

Recycled concrete also referred to as waste concrete is used here to refer to the benefical use of concrete for more than a single cycle of use. Once a concrete structure must be removed to make room for some new activity at the site which it occupies it may or must be removed. When such removal takes place, much more often than not, the rubble is regarded solely as unwanted solid waste that needs to be disposed of by transportation to a disposal site with minimum handling, processing and transportation. Only rarely had the old concrete been regarded as useful raw material for use in new construction.

The idea that demolished concrete and building rubble could be used as an aggregate for concrete was conceived in the days immediately following world war II. The reasons are not far fetched. At that time equipment to work aggregate quarries was difficult to come by in most European countries with war shattered economies. Problems of transportation were quite acute. And the volume of rubble to be removed from the sites of bombed out buildings and military fortifications was so great as to require consideration of alternatives.

As a result rubble left after the bombardment of cities was used in concrete for rebuilding, particularly in Britain and Germany. However as soon as more affluent days appeared, just a few years later, the compulsions to press ahead with the investigation, which were still inconclusive, no longer existed.

Since that post-war period there was little research interest in the use of Recycled concrete as a source of aggregate, until the late seventies, when for diverse reasons fresh interest was evinced in Western Europe and United States of America (USA) in this subject. In some areas, heavy urban expansion had depleted deposits of aggregates (such as natural sand, gravel, stone, and air cooled iron blast-furnace slag) available from sources close to the sites of work, thereby entailing excessively costly transportation over long distances. In other areas, new construction programmes, involving the replacement of old buildings, are once again making available substantial quantities of demolished concrete, the disposal of which is in any case a major problem. For example, Frondistou-Yannas (1977), reported that in USA alone, demolition wastes amount to over 27 million tonnes a year, and concrete accounts for nearly 75 per cent of this quantity.

Perhaps, the most pressing reason of all is that many countries have legislated and strictly enforced stringent anti-pollution and environmental regulations which restrict the number of new quarries that can be opened and also require restoration of those which have been worked.

Under the pressure of these problems, studies have been undertaken on the basic properties of concrete in which natural aggregates are substituted by recycled aggregates from waste concrete and rubble. Some studies have been based on concrete mixes that contained the demolished concrete as the coarse aggregate component only with natural sand forming the fine aggregate. In other investigations, the study was extended to cover crushed waste concrete as fine aggregates as well. The outcome of these investigations indicate that recycled concrete aggregate can be used as substitute for natural aggregate.

The word "Gap-grading" used here, is also referred to as single-size grading or intermittent grading. It is the omission of undesirable intermediate sizes within a narrow range of maximum allowable size of the coarse aggregate and the largest admissible size of the fine aggregate, and the deletion of the extreme fines from the conventional continuous gradings. The main aim of grading is to permit the voids in the compacted coarse aggregate particles in a given volume of concrete to be filled

up by the compacted fine aggregate particles, and in turn, to allow the remaining voids in the system of compacted coarse and fine aggregates to be filled up by cement paste at a stipulated water-cement ratio, with adjustment for admixtures if used, to meet the strength requirement. This can be best achieved through gap-grading, particularly for stiff mixes with low water-cement ratios such as are required for high-strength concrete. Gap-grading of aggregates allows full compaction of the plastic concrete, and achieves an optimum void filled concrete. Such a fully compacted or optimum void filled concrete will have increased compressive strength.

The results of studies on recycled concrete indicate that the concrete containing the recycled concrete aggregate has a lower compressive strength when compared to the original concrete. Work to find ways of improving the compressive strength and other physical properties of recycled concrete has been in progress in a number of places for some time. The results available indicate that Recycled concrete makes satisfactory concrete aggregate, and the characteristically lower strength of concrete mixtures that contain recycled concrete aggregate may be increased by the use of a water-reducing admixtures, to lower the water content of mixture that contains recycled concrete.

Gap-grading is employed in this work to produce Recycled concrete and a study is made on its effect(s) on the strength of recycled concrete.

1.2 Significance of The Research

Replacements for conventional aggregates has continued to be a focus of research interests in many parts of the world for some times now. In this country most urban areas already have problems of obtaining adequate aggregate supplies and difficulties of disposing of concrete rubble produced from demolished buildings. The present scarcity and excessive costs of conventional aggregates in some parts of the country is expected to keep increasing and become more acute and extensive in the near future. Presently the need for research into alternative materials had been identified. The Federal Government has continued to challenge and encourage institutions of higher learning and Research establishments to focus research interest on low cost replacement for conventional materials. In this Department several research works have been carried out on the possibilities of using organic and industrial wastes in concrete production with possitive results indicating improved properties of concrete in some cases. It is hoped that the result of this research will contribute meaningfully to existing knowledge and understanding of recycled concrete aggregates and also serve to stimulate indiginous technical progress.

1.3 Aim

Previous works have shown that the compressive strength of concrete mixtures containing recycled concrete was lower than that of companion control mixtures. The aim of this research is to investigate whether this lower strength could be increased by modification in the grading of the concrete mixture.

1.4 Scope And Limitations

The main property to be tested in this investigation is the compressive strength as indicate by cube-crushing tests. This is because many of the other desirable properties of concrete often improve with an improvement of its compressive strength value. Tensile strength as indicated by cylinder-splitting tests were also obtained from specimens of 28 and 90 days maturity. The scope of this research was limited by non availability of major equipment of concrete research in the Department of Building Laboratory at the time of this research.

1.5 Methodology

One concrete containing 20 mm max. size crushed Zaria granite as coarse aggregate and natural sand as fine aggregate was recycled into aggregates.

Four types of concrete were produced from the recycle concrete aggregates by introducing three different gaps in the aggregates grading and also retaining the original continuous grading used in the production of granite concrete: All other factors were kept essentially identical.

The original granite concrete was tested in compression and tension (by cylinder splitting test) after 28 and 90 days curing in water under normal conditions. After 90 days maturity granite concrete was crushed, screened, recombined and used as recycled coarse aggregate of 20 mm max. size in the production of the four types of concrete. Natural sand was used as fine aggregate in the production of the new concrete.

All recycled-aggregate concretes were cured under water at normal conditions and tested at 7, 28 and 90 days maturity in compression and at 28 and 90 days maturity in tension.

Chapter 2.

LITERATURE REVIEW

Several items relating to past use of old concrete as aggregate and Gap-grading of concrete aggregates were found and reviewed below.

2.1 Concrete Recycled As Aggregate For New Concrete

Three major works of previous research into concrete recycled as aggregate were referred to among others by Buck (1977).

(i) The work of Gluzhge: Gluzhge worked with waste concrete in Russia in 1946. His conclusions were: (a) New concrete will be no better than waste concrete that is used as aggregate. (b) The use of concrete fines as sand requires an undue increase in the cement content of a mixture. (c) Compressive strengths are lower when concrete is used as aggregate. (d) The specific gravity of crushed concrete aggregate tends to be lower than that of natural aggregates. (e) The cement factor can be lowered if the crushed concrete aggregate is moistened, not saturated, before use. (f) For equal compressive strengths, the flexural strength of mixtures with crushed concrete aggregate is higher than for control mixtures. (g) Mixtures with crushed concrete aggregate stiffen rapidly but consolidate well with vibration.

(ii) The work of ploger: Ploger studied the compressive strength of waste concrete in 1947, by recycling two concretes into aggregates. He made three mixtures: one contained coarse and fine aggregate from a natural gravel concrete, each of the others contained one of the recycled concretes as coarse aggregate with a natural sand. His curves for compressive strength versus water cement ratio and cement factor were quite similar to those obtained from concretes of normal composition. His curve for compressive strength versus water cement ratio is shown in Fig 2.1.

(iii) The work of Graf: Graf studied the recycling of building rubble in Germany in 1948. As part of this work he examined the effects of contamination by gypsum plaster by the addition of different amounts and sizes of gypsum to rubble. He concluded that 1 per cent sulfur trioxide (SO_3) was a maximum tolerable level, and that powdered gypsum appeared to cause more and faster reaction than gypsum grains between 1 and 7 mm in size. He also found that the period of dry curing was beneficial in reducing expansion.

There were a number of other papers in the European Literature that dealt significatly with the use of crushed concrete as concrete aggregate.

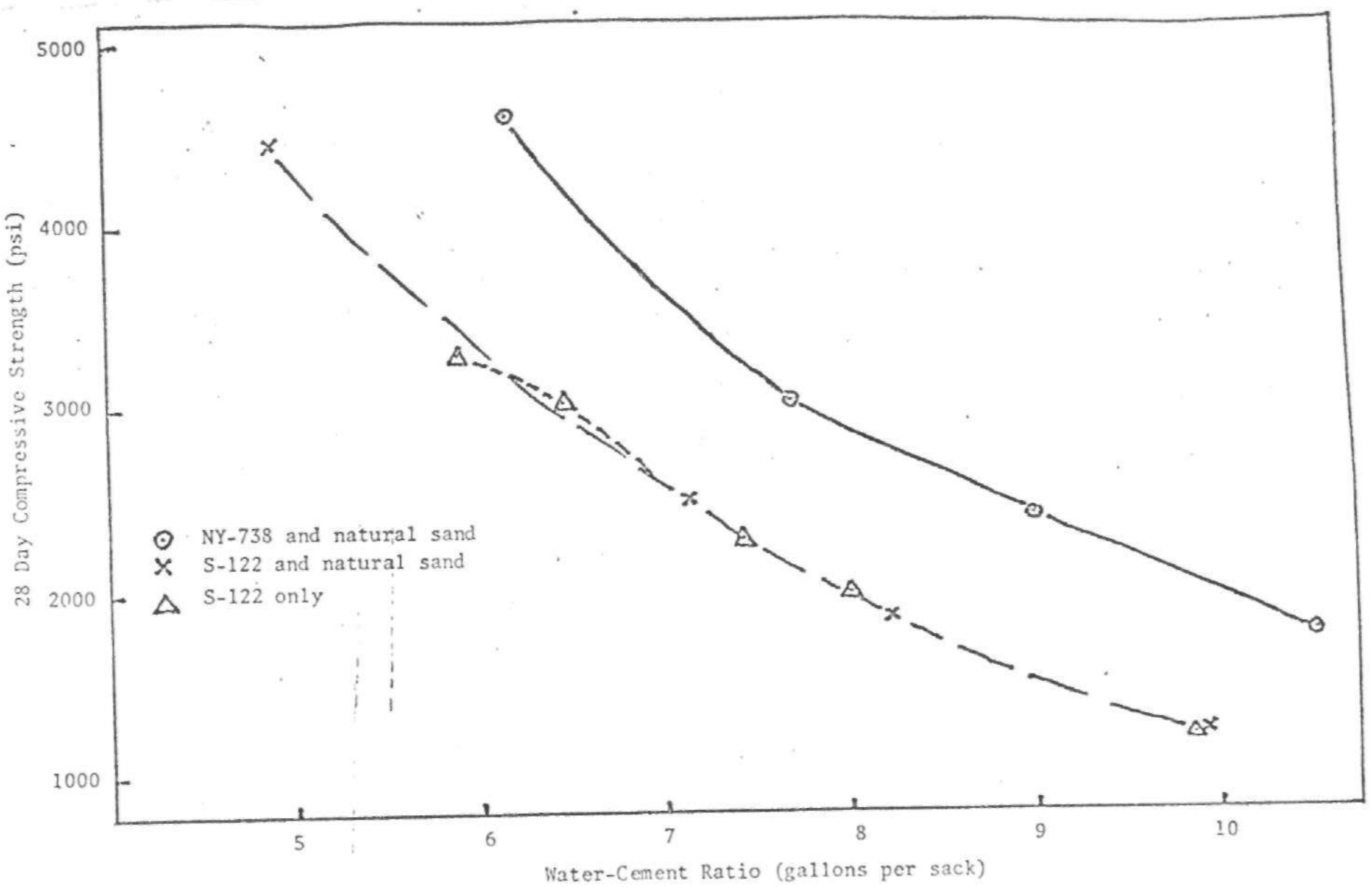


Figure 2.1. Comparison of Water-Cement Ratio Compressive Strength Curves (modified after Ploger, Buck (1977))

Lydon (1975) reports that old concrete was crushed and used in an air-entrained pavement quality concrete with about 300kg cement per cubic meter (m^3) concrete and 6 per cent air. This was compared with a control concrete of similar cement content. Some loss of strength was evident - about 20 per cent - but moisture, temperature, and volume changes were similar and, perhaps more significantly, freezing and thawing performance of recycled concrete were much improved.

Buck (1977) recycled concrete mixes that originally contained siliceous aggregates and concrete that contained carbonate-rock aggregates. His concrete mixtures were like that of ploger. They contained all recycled concrete as aggregate or included a natural sand as fine aggregate. He studied the Compressive Strength, frost resistance and volume stability of recycled aggregate concrete using a constant water-cement ratio. He found that aggregates made from old concretes tends to have high absorption, low specific gravity and produced concrete of lower compressive strength. He observed that recycled concrete can best be used as a substitute for coarse aggregate only, and that recycled concrete waste might be a satisfactory replacement for natural aggregate.

2.1.1 Properties of Concrete Aggregate

Aggregates, the major constituent of concrete, are critical to the performance of both freshly mixed and hardened concrete. When they perform below expectation, unsatisfactory concrete may result. Their important role is frequently overlooked because of their relatively low cost as compared to that of cementitious materials.

According to Walker and Bloem (1960) and Gordon and Gillespe (1963) there are experimental evidences to show that at fixed water-cement ratio strength decreases as maximum size of aggregate particularly for sizes larger than 38 mm. However, for the same cement content, this apparent advantage of the smaller size may not be shown because of the offsetting effects of the required increased quantity of mixed water.

Tuthill (1980), observed that by limiting the amount of materials passing the 3/8 in. (9.5mm) sieve in the coarse aggregate, the concrete properties of workability, pumpability, finishing, and response to vibration are improved. Kar and Day (1974) studied the strength of partially Gap-graded concrete using six aggregate gradings selected arbitrarily (three with 20 mm maximum size). They found that the affects of the aggregate grading on concrete strength is not insignificant, and that concrete of the same water/cement and aggregate/cement ratios may

have different tensile and compressive strengths depending on the grading of the all-in-aggregate, stiffness, shape and surface texture of the aggregates.

Fine Aggregate: Fine aggregate grading, particle shape, and amount all have a major influence on the strength of concrete because of their effect on water requirement. With a rudimentary knowledge of solid geometry, one can easily examine the surface area, and solid volume of any equivalent diameter size D, which are respectively πD^2 and $\pi D^3/6$, giving the specific surface, (surface per unit volume) as $6/D$. Thus the larger the diameter, the less is the specific surface, and vice versa.

Fine aggregates contain a much higher surface area for a given weight than do the larger coarse aggregates. Since the surface area of all the aggregate particles must be coated with a cementitious paste, the proportion of fine to coarse can have a direct quantitative effect on paste requirements and normally have made it more economical. Such proportions also have made it possible to produce higher strengths for a given amount of cementitious materials. However, if the proportion of sand is too low, serious problems in workability become apparent. Consolidation by means of mechanical vibrators may help to overcome the effects on an undersanded mixture, and the use of power finishing equipments can help to offset the lack of trowellability.

Recycled Concrete Aggregate: The properties of recycled concrete aggregate have been reported by Ploger, Buck and Malhotra. A summary of their results which also includes fresh natural aggregates for comparison is reproduced from Nixon (1979) and shown in table 2.1. The most marked difference in the physical properties of the recycled aggregates is their tendency to have a higher absorption compared to the natural aggregate from which the debris concrete was originally made. This characteristic is more marked when the debris is crushed to fine aggregate size. For example, in Table 2.1, where the natural sand had a water absorption of only about 0.5 per cent, the waste concretes crushed to fine aggregate absorbed water to the extent of 8-10 per cent of its own weight. This characteristic is, presumably, due to the porosity of the cement paste adhering to the old aggregate particles, which will tend to be more concentrated in the finer fractions. Obviously, the most marked effect will be on the loss in workability of the concrete between the time of mixing and its compaction in the form. The density of the recycled concrete aggregate is also lower but not as marked as the difference in absorption.

Table 2.1: Physical Properties of Aggregates Made From Recycled Concrete and Comparision With Properties of Fresh Natural Aggregates (Obtained From Nixon (1979)

Description	Original Concrete Compressive Strength (MN/m^2)	Absorption (%) Coarse aggt.	Fine Aggt.	Relative Density (SSD) Coarse aggt.	Fine Aggt.
Ploger					
Gravel & sand aggregate	35 (90 day)	6.0	10.5	+ nd	nd
Trap rock coarse aggt. mixed crushed and natural sand fine aggt.	34 (90 day)	4.5	nd	nd	nd
Buck					
Driveway waste (chert aggt.)	41 (8 years)	4.5	7.9	2.42	2.33
Discarded beam (carbonate coarse aggt.)	55 (9½ months)	3.9	nd	2.52	nd
Discard beam (granite coarse aggt.	13 (2½ years)	2.3	7.9	2.59	2.36
Concrete pannels (chert gravel aggt.	23 (8 months)	4.4	7.5	2.36	2.27

Table 2.1 contd.

Original Description	Concrete Compressive strength (MN/m^2)	Absorption (%) Coarse aggt.	Absorption (%) Fine aggt.	Relative Density (SSD) Coarse aggt.	Relative Density (SSD) Fine aggt.
Malhotra					
Discarded test cylinders	High	4.0	7.9	2.53	nd
(limestone coarse and sand fine aggt.)	Medium	3.9	9.3	2.53	2.31
	Low	4.4	8.6	2.5	2.34
FRESH NATURAL AGGREGATES					
Limestone		0.4		2.68	
		0.8		2.67	
Chert gravel		2.6		2.62	
			0.5		2.7
Natural sand			0.4		2.63

+ nd not determined

2.1.2 Physical Properties of Recycled Concrete

Two states of the material are of the utmost importance when appraising the properties of concrete: Firstly the freshly mixed state, in which the properties of interest are those that govern ease of transport and placing of mix in the required location, and secondly the hardened state, in which knowledge is needed of the ability of the material to carry the required loads and stresses. The properties of the two states are interrelated, since the final strength of a given concrete mix is greatly affected by the degree of compaction that was achieved when the fresh mix was placed in position.

Workability: Workability is used here as a collective term to include all the essential properties of the concrete in the plastic condition. These properties determine the ease with which full compaction and placing can be obtained. Workability of concrete according of Hughes (1960) is known to depend upon: (i) the cement; (ii) the aggregate; (iii) the relative proportions of the constituents; and (iv) the time and temperature of mixing.

Concrete mixes containing both coarse and fine fractions of recycled aggregates have been found to give a lower consistency and to require a higher cement content compared to the corresponding control mixes. The effect is most marked when material finer than 150-microns from the recycled aggregates, which comprises mainly of hydrated cement particles is used.

If, however, natural sand is substituted for the recycled fine aggregate, little deference has been observed in the consistency, air content or cement content of the concrete mix.

Buck was reported by Nixon (1979) to have observe that mixes containing crushed concrete as both coarse and fine aggregate had a lower slump and higher cement content than the control mixes. When however natural sand was used as the fine aggregate with waste concrete coarse aggregate there was little difference in slump, air content, or cement content from the equivalent mix made with new aggregate. The work of Frondistau-Yannas (1977) confirms these observations.

Bond Strength between Crushed Concrete Aggregate and Mortar:

Frondistou-Yannas (1977) studied the aggregate-matrix bond strength for fresh granite gravel, granite gravel sorted from the crushed concrete, granite gravel with adhering mortar and of crushed mortar from the concrete. She observed that failure of specimens made of gravel, whether new or recycled, occured always at the aggregate-mortar interface, while specimens containing recycled mortar as the aggregate always involved fracture of the later. Her results show a decreasing bond strength with increasing proportion of mortar, emphasising the desirability of reducing the proportion of mortar in the recycled concrete aggregate.

Effects of Admixtures in Original Concrete: Hanson and Hedegard (1984) studied the properties of recycled-aggregate concretes as affected by admixtures in original concretes. Five almost identical concretes were designed and produced with four different kinds of admixtures. A control mix was made without admixtures, and the other four mixes contained superplasticizing, an air-entraining, an accelerating, and a retarding admixture. Strength, consistency, air content and setting of old and new concretes were compared. Chloride contents were also determined for recycled aggregates produced from original concretes containing the accelerating admixture. They found that the admixtures used in their investigation had little or no effect on the compressive strengths of hardened, recycled aggregate concretes when added to original concretes at or above, maximum dosages recommended by the manufacturers.

Effect of Impurities in the Concrete: So far, most investigations on this aspect have concentrated on the effect of sulphate impurities, presumably originating from gypsum plaster. This problem cannot, however, be viewed in isolation as the chemical composition of the cement used in the new concrete will also exert influence on the end result. A Japanese investigation suggests that under exposure to humid conditions, the maximum total sulphate content that can be tolerated as part of the aggregate is 0.6 per cent by 0.7 per cent with sulphate-resistant cement.

However, as the sulphur trioxide content of any portland cement differs from source to source, it is considered better to set the limit on the basis of the total sulphur trioxide content of both the cement and the aggregates. On this basis, maximum sulphur trioxide content of 5.2 per cent by weight of cement is recommended.

Drying Shrinkage: Aggregate has a major effect on the drying shrinkage of concrete. Cement paste has a high shrinkage potential and aggregate introduced into the paste either to make mortar or concrete, reduces paste shrinkage due to the restraint provided by the aggregate. The resulting shrinkage of the concrete is a fraction of the shrinkage of the paste due to this restraint of the aggregate.. From this it is concluded that the shrinkage of concrete under given drying conditions is dependent on the shrinkage potential of the paste and the properties and amount of the aggregate.

Hasaba et al were reported by Hansen and Boegh (1985), to have found drying shrinkage of a recycled-aggregate concrete made with corase recycled aggregate and natural sand to be 50 per cent larger than dying shrinkage of a corresponding control concrete made with conventional aggregates. When both coarse and fine recycled aggregate was used, drying shrinkage of the recycled-aggregate concrete was 70 per cent larger than that of the control.

Modulus of Elasticity: Most demolished concrete can be converted into aggregates for the production of new concrete, but deformational properties of recycled-aggregate concretes are different from those of conventional concrete because of old cement mortar that remains attached to natural aggregate particles in recycled aggregates after crushing.

Frondistou-Yannas (1977) found that recycled-aggregate concrete made with coarse recycled aggregate and naturalsand had up to 40 per cent lower modulus of elasticity than conventional concrete. According to Hansen and Boegh (1985), Mukai et al reported between 20 and 30 per cent lower modulus of elasticity for a wide range of recycled aggregate and natural sand than for conventional control concretes. Hansen and Boegh (1985) found that recycled-aggregate concretes made with coarse recycled aggregate and natural sand have between 15 and 30 per cent lower static and dynamic modulus of elasticity than corresponding conventional concretes. The reduction in the modulus of elasticity is attributed to the fact that recycled aggregates have, themselves, a lower modulus than natural aggregates and this, in turn, affects the modulus of the concrete.

Durability: For many conditions the most important property of concrete is its durability. There are many aspects of concrete durability, and practically all are influenced by properties of the aggregate. Various properties related to the pore structure within the aggregate particles, such as absorption, porosity, pore size and pore

distribution, or permeability, may be indicattors of potential durability problems when used in concrete which will become saturated and freeze in service. Buck (1977) found that the freeze/thaw resistance of the concrete made with recycled concrete aggregate were very similar to that of control concrete. The work of Malhotra as reported in Mixon (1979) confirm this similarity. Buck also measured the 28 day linear coefficient of thermal expansion and monitored the length change of prisms stored at greater than 90% relative humidity (RH) and $23 \pm 1^{\circ}C$ The results of these tests on concrete containing recycled concrete aggregate showed their behaviour to be very similar to control concretes.

Strength: Perhaps the second most important property of concrete and the one of which values are most frequently specified, is strength. The types of strength usually considered are compressive and flexural.

Strength depends largely on the strength of the cement pasted and on the bond between the paste and aggregate. The strength of the aggregate also affects the strength of the concrete, but most normal weight aggregates have strengths much greater than the strength of the cement paste in which they are used. So far as the physical properties of concrete made with recycled aggregates are concerned, there is no doubt that, while it conforms to the water-cement ratio law and gains strength with age,

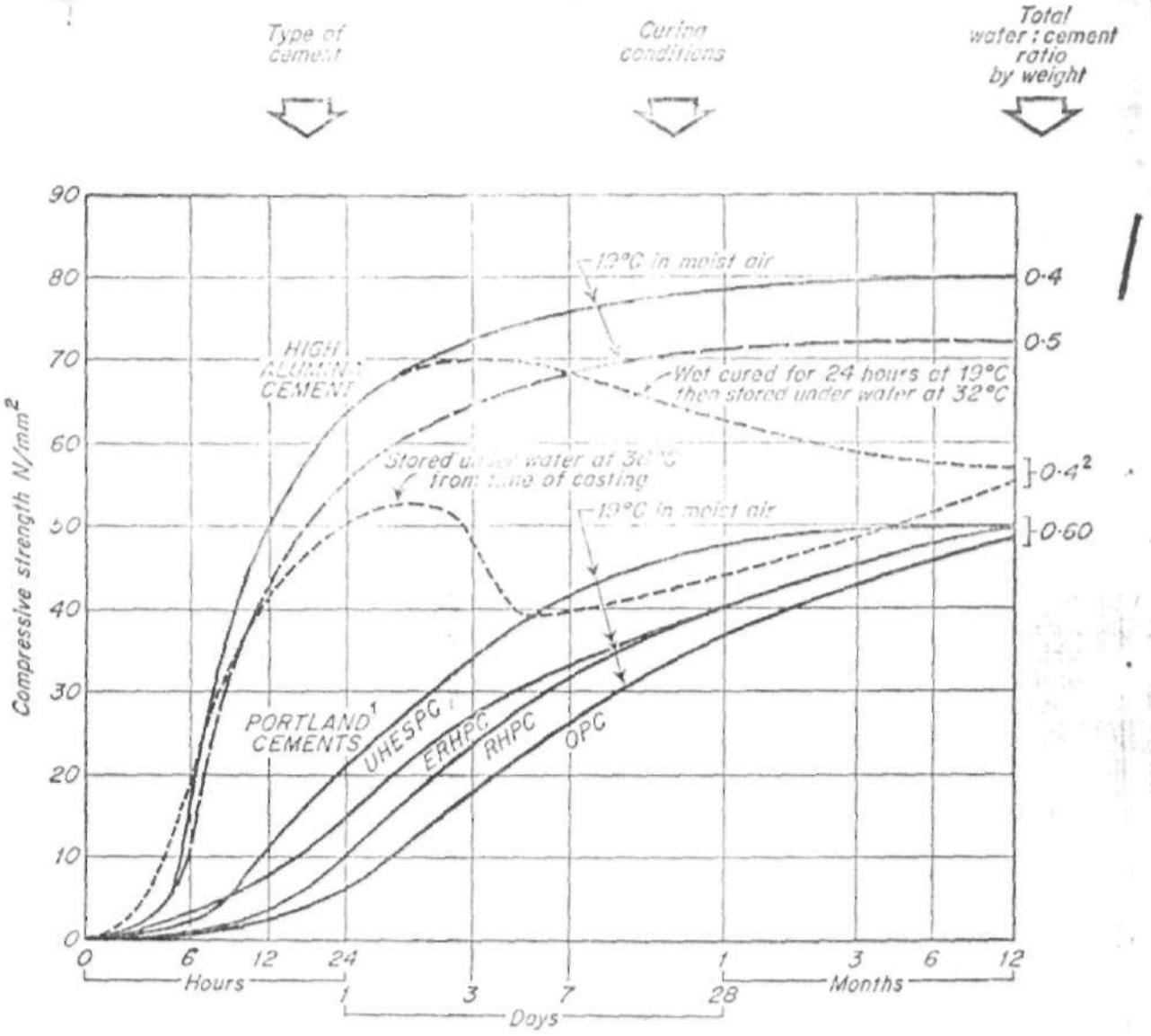
It has a lower compressive strength level than a conventional concrete at the same water-cement ratio and equal workability. While the precise reasons for the loss in strength are yet to be fully understood, it has been observed that, when the concrete fails, it is the adherent mortar on the recycled aggregate that appears to be the weakest link.

Frondistou-Yannas (1977) studied the variation of strength with water/cement ratio of concrete made with crushed concrete coarse aggregate. The old concrete was made with a granite gravel. In general her results confirm the findings of previous authors that the concrete containing the recycled concrete aggregate has a lower compressive strength.

Buck (1977) studied the compressive strengths of concrete containing recycled concrete aggregate at constant water/cement ratio and constant workability. In general he found lowered strengths compared with a control mix and was able to show that the strength of the concrete can be higher than the original strength of the crushed concrete which comprises the aggregate. Standard curves of strength development of concretes made with various cements are shown in Fig 2.2.

2.1.3 Processing of Waste Concrete into Aggregate

Basic physical and chemical characteristics of aggregate cannot generally be altered by processing, although the qualities of certain deleterious particles



¹ Types of Portland cements (PC)

UHESPC	ultra high early strength
ERHPC	extra rapid hardening (RHPC with calcium chloride has similar properties)
RHPC	rapid hardening
OPC	ordinary (white, coloured and sulphate resisting Portland cements have similar strength properties).

² 0·40 is the maximum water : cement ratio advised for high alumina cement concrete subject to high temperature and humidity. Loss of strength at high temperature and humidity is greater at higher water : cement ratios.

Note: Higher strengths in thoroughly compacted concretes are obtained at all ages with lower water : cement ratios. Strengths of 'green' concrete are difficult to measure.

Fig.2. Strength development of concrets made with various cements (obtained from Alan (1975)

can be reduced. Aggregate characteristics that can be controlled include grading, moisture content, cleanliness, removal of abnormally light particles, and to some degree, particle shape. Economic factors usually determine the degree to which processing can be directed to produce the best compromise between desirable aggregate properties and economy. Problems associated with the processing of waste concrete are the problems of dust, noise and removal of steel.

Equipment:- Conventional demolision equipment have been used for initial break-up of implace pavement. Buck (1977) observed that portable crushing plants have been employed in operations that may require a crew to cut and remove reinforcing bars or wires to free the concrete fragments between initial break up and loading or other movement.

Public works magazine for October, 1972, reported two washing-ton D.C. firms that were engaged in producing useable aggregate products from demolished roads, concrete construction and excavation material at rates varying from 100 to 200 tons per hour. Sadler (1973) reported of the success of a plant for crushing demolition concrete located at Minneapolis - St. Paul Internation Airport (see Plate 1). Included in the actual crushing operation were a primary jaw crusher with vibrating pan feeder, a cone secondary crusher, a 37.0m shacker, a 150 - kw trailer mounted generator, a two-deck vibrating screen

A CRUSHING SUCCESS: Aggregate from Concrete



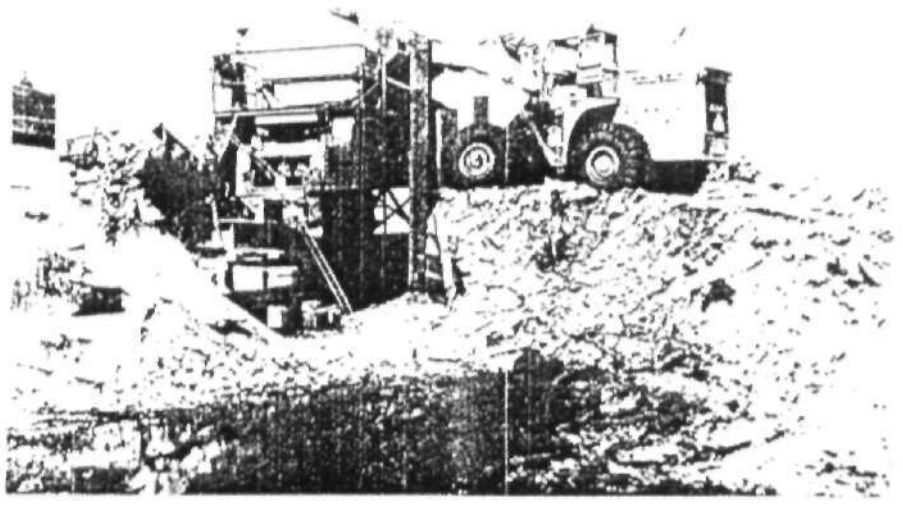


Plate I: PLANT at Minneapolis-St. Paul International Airport utilized primary jaw crusher and secondary cone crusher to reduce demolition rubble to make useful aggregate. (after Sadler, (1973))

plant and three 76.0cm by 15.0m rubber conveyor belts. The work of crushing concrete proceeds at a rate of some 200 tons per hour. The crushed material possessed a high degree of uniformity and showed no tendency to solidify in the stock pile.

The use of adjustable hydraulic breaker machines (see Appendix III) for demolision of concrete structures in Japan was reported by Buck (1977). This group of machines are reported to be quiet, clean and free from shock. Buck (1977) made mention of a novel machine called the Nibbler used for quiet break-up of old concrete. It can break up to 65 yd^2/hr (53m^3/hr) of 10 in (approx 25 cm) thick concrete. Its breaking mechanism is said to be similar to that used by a person breaking a bar of chocolate.

2.2 Gap-graded Concrete

In the mix proportioning process, the concept of minimum voids and the principle of minimum surface area are basically in conflict with each other. The former implies that a blend of several fractions of coarse aggregate is always superior to a single fraction. The later states that for a given maximum size of aggregate a single fraction is superior to any blend. Between the two extremes - continuous gradation, on the one hand, and a single fraction of coarse aggregate, on the other lies the vast and largely unexplored gray area of gap-graded mixes.

Neville (1981) defined Gap-grading as a grading in which one or more intermediate size fractions are omitted. The term continuous grading is used to distinguish conventional grading from gap-grading. The aim of Gap-grading is to achieve strength from the efficient packing of the aggregates and the principle employed is to omit certain 'undesirable' sizes of aggregates from the gradings specified by the relevant British Standards. Such undesirable sizes are those which prevent the effecient packing of the other sizes.

2.2.1 Historical Notes On Gap-Graded Aggregates

The original idea of "Gap-grading" or "jump gradings" or "discontinuous mixtures" in mortar and concrete aggregates seems to date back to early 1890s. Mercer (1943) quoted M. Feret as saying that: "As always one rediscovers the law of discontinuous mixtures (i.e., jump gradings) which I proposed some fifty years ago which is still so greatly contested". Feret's investigations on the granulometric composition of sands dominated the early history of concrete aggregate grading. His conclusion for sand mortar was that the best mixture of sand and cement for mortar is made up of coarse and fine grains only, with no intermediate grains.

According to Mercer (1943), the findings of other research workers such as Prof. McNeilly of vanderbilt University, S.W. Thompson, J. Bolomey and A. Caquot confirmed the conclusion of Feret and tend to support its application

in the design of concrete mixes. For example, Prof. McNeilly had concluded in 1945 that: "The best sizing of grains in a commercially-sieved aggregate is about as follows: 53 percent to be caught between the 4.00mm and 1.70mm sieves; 47 per cent fines to be passed by the 4.00mm sieve (this includes the cement). There is reason to believe that the coarse aggregate in concrete could be beneficially sized on a basis similar to the above; that is to say, there should be a jump in the size from coarse to quite fine instead of the usually accepted graded material."

Previous Application of Gap-graded Concrete: Li (1967), reported that one of the earliest practical applications of gap-graded aggregates on a large scale was in concreting the calderwood tunnel of the calderwood hydro electric development of the Aluminum Company of America. There was no coarse aggregate finer than 20mm and no fine aggregate coarser than 4.00mm and the average tested strength at 28 days was approximately 28.0N/mm^2

Other earlier practical application cited by Mercer (1943) are the Railroad terminal at Los Angeles, and the Edison Memoral Tower. John J. Early who was entrusted with the work of providing a permenent concrete facing for the Edison Memorial Tower was quoted as saying that: "the properties of discontinuous mixtures are unique and that, all of other things being equal, they are to be preferred over other known types of gradation for aggregates".

Li, (1967) also observed that for many years gap-graded aggregate concretes have been used for the thin facing layer of precast exposed aggregate concrete members with excellent results. Further applications of low-slumps, gap-graded aggregate mixes were reported by Litvin and Pfeifer (1965) after achieving attractive uniform exposed aggregate surfaces of cast-in-place concrete; they are the Hollymatic corporation building at Park Forest III; the American Republic Insurance Company Office building at Des Moines, Iowa; and Maine Township High School South Complex in Park Ridge, III.

2.2.2 Physical Properties of Gap-graded Concrete

The most important properties of concrete are its compressive strength and durability in the hardened state and its workability and cohesiveness in the plastic state. Other properties of the hardened concrete tend to improve as the compressive strength and durability increase. For example, flexural strength, tensile strength, shear strength and bond strength are closely related to compressive strength, and water tightness will be obtained if the concrete is to have satisfactory durability.

Other things being equal, the strength of fully compacted concrete at a given age depends mainly on the water/cement ratio. This attributed to the weakening effect of the greater amount of the excess water which does not combine with the cement, and which produces a more porous structure whether it has evaporated or not. The strength is also affected by the aggregate but to a lesser

extent and in a more complicated way. The strength depends also on the richness of the mix in such a way that a leaner mix, which gives a lower workability for the same water/cement ratio, results in a slightly higher strength.

Li, (1967) and other investigators have examined the characteristics of Gap-graded concrete. They claim that the absence of many intermediate-size aggregates gives the following advantages (among many others) in gap-graded concrete:

i. Reduced specific surface area in gap-graded aggregates, as a result of high percentage of coarse aggregate and low percentage of fine aggregate: hence requiring less cement paste and lower water/cement ratio than in continuously graded aggregates.

ii. Better workability for given amount of cement and water/cement ratio: hence making leaner mix than conventional concrete of equivalent strength feasible.

iii. Dryer mix than conventional concrete of equivalent strength feasible, hence lower slump concrete which is conducive to excellent strength and elastic properties and therefore less drying shrinkage than in conventional concrete.

iv. Stronger compressive strength and flexural strength as a result of lower slump and transmission of stress through particule contact of the coarse aggregate which is generally stronger than sand and hardened cement paste.

v. Higher modulus of elasticity as a result of reduced specific surface area, less cement paste, lower water/cement ratio and lower slump than in conventional concrete, which reduces deflection. In comparison with equal strength Elgin gravel concretes using graded aggregates, the modulus of elasticity obtained by Litvin and Pferfer (1965) are 10 to 30 per cent higher.

vi. Lower creep than in conventional concrete, which again reduces deflection. Litvin and Pfeifer (1965) observed ultimate creep for Elgin gravel concretes of equal strength: their gap-graded concrete had lower slump and creep than previous studies for conventionally graded concrete.

vii. Excellent durability; This property according to Li (1967) was shown by Isberner in precast exposed aggregate concretes of mix proportions similar to Litvin and Pfeifer's (1967); and more economical concrete as a result of less cement (and less number of stockpiles or storage bins being needed) than a conventional mix of equal strength.

2.3 Design of Concrete Mix

Dhir and Jackson (1984) defined concrete mix design as the procedure by which, for any given set of conditions, the proportions of the constituent materials are chosen so as to produce a concrete with all the required properties for the minimum cost. Cost was used in this context to include the sum of the cost of materials, the cost of the mix design, of batching, mixing and placing the concrete and of site supervision.

Sydney (1977), observed that, there are two fundamentals of mix design, the choice of water cement ratio and the aggregate grading, which must be taken into account when designing a mix.

2.3.1 The Design of Gap-grading

The object of Aggregate grading design is to achieve, by proportioning the component sizes, a minimum void or a low controlled-void mixture. Ramakrishnan (1977), observed that honeycombed zones in concrete are sometimes due to the inability of a too coarse fine aggregate concentration. Therefore, the choice of a fine aggregate smaller than the critical size of entrance ensures that these voids do not remain empty but get filled by the migration of fine particles through the inter-void throats. The principle lies in the selection of the 'permissible' and 'admissible' sizes contitutes the criterion for gap-grading.

For plain and mass concretes the maximum permissible size will depend on the equipment used for handling, mixing and conveyance, and the available vibrating devices for effective consolidation. For reinforced and prestressed concrete, the maximum permissible size of the coarse aggregate will be limited by its free passage through the spacings of the steel or ducts, and the clear cover required. According to Li (1967), if singled-sized spheres representing the coarse aggregate are compacted under vibration into a container they tend to take up a rhombohedral form of packing. Bate and Stewart (1955) and Li (1967) have shown through their works as well as the results of other researchers that in rhombohedral form of packing, the largest admissible size of fine aggregate for serving its function properly as a filler material is equal to 0.155 D where D is the diameter of the largest size coarse aggregate used.

Table 2.2 reproduced from Lydon (1972), indicates the maximum sand particle sizes that can be reasonably used with relevant coarse aggregate sizes in the design of Gap-grading. Bate and Steward (1955) have advocated the choice of gap-graded material for concrete on the grounds of its superior packing properties, and also noted that while there are certain ranges of mixes for which gap-grading might be advantageous, it is not generally considered that the design of such mixes represents any real substantial departure from or has any generalised positive improvements over the normally accepted procedure of concrete mix design.

Water/Cement and Aggregate/Cement Ratios: The strength of concrete at a given age and cured at a prescribed temperature is assumed to depend primarily on two factors only: the water/cement ratio and the degree of compaction. In order to obtain concrete of maximum strength and durability, good compaction is essential. This can only be achieved if the concrete has an adequate degree of workability in relation to the methods of compaction to be used. Rama Krishnan (1977), had remarked that for high strength concrete, the water-cement ration selected should be the minimum which would give the quantity of water sufficient to hydrate the cement paste, without any excess which may cause bleeding, after the water required for lubrication and saturating the aggregates to a surface-dry condition has been supplied. He also confirmed that the compressive strength of concrete at constant water-cement ratio increases with an increase in the aggregate-cement ratio as long as full compaction can be achieved. Tables 2.3 and 2.4 reproduced from Lydon (1972) provide guidance for the selection of suitable aggregate/ cement ratio for required water/cement ratios for River aggregate and crushed rock aggregate respectively. The tables were obtained from previous works on the design of gap-graded concrete mixes.

Table 2.2: Recommended Sizes of Sand for gap-grading

Coarse aggregate	Sand
37.5 - 20.0 mm	All passing a 2.36 mm sieve
20.0 - 10.0 mm	All passing a 1.18 mm sieve
10.0 - 5.0	All passing a 600 mm sieve

Table 2.3: Aggregate/Cement ratio and Water/Cement ratio for river aggregate of different maximum sizes

	Aggregate/Cement ratio(by weight)						Maximum aggregate size (mm)
	3	4	5	6	7	8	
Water/cement	0.32	0.36	0.39	0.42	0.46	0.50	37.5
ratio (by	0.32	0.36	0.40	0.44	0.49	0.56	20.0
weight)	0.37	0.42	0.47	0.52	0.59	0.67	10.0

Table 2.4: Aggregate/Cement ratio and Water/Cement ratio for crushed rock aggregate of different maximum Sizes

	Aggregate/cement ratio (by weight)						Maximum aggregate size (mm)
	3	4	5	6	7	8	
Water/Cement	0.34	0.38	0.41	0.46	0.52	0.58	37.5
	0.34	0.39	0.43	0.48	0.55	0.62	20.0
Ratio (by weight)	0.40	0.47	0.54	0.61	0.69	0.77	10.0

2.3.2 Particle Size Distribution

Hughes (1960) reported that aggregate grading is known to have a major effect upon certain physical characteristics of concrete. Particle size distribution or grading of aggregates, affects not only water requirement of concrete but such qualities such as economy, strength, finishing characteristics and workability.

Choice of Aggregates: Provided that the particles of the aggregates are clean, resistant, durable, and the dust content (that passing the 150μm-sieve) limited to a few percent, good concrete can be made with a wide range of grading and the choice of aggregate should largely be a question of economy.

Combined aggregates with one or more size groups absent are normally called gap-graded aggregates. Each size group absent is considered one gap. According to Singh (1959), such aggregates with two or three succesive gaps (within the extreme size groups) suffer a few disadvantages compared to continuous grading. As a general rule, three successive gaps should be avoided for wet mixes as there is a marked tendency for such mixes to segregate. However, if concrete of stiff consistency is required and is to be placed by vibration, Singh (1959) observed that the latter grading may even be used with advantage and give properties not obtained with continuous grading.

Sieve Analysis: The most common way of measuring the percentage of each size particle in a sample of aggregates is by sieve analysis. The sample is passed through a series of

sieves that have decreasing sizes of mesh. The amount of each size particles can be determined by weighing the material retained in each sieve.

2.4 Materials For Concrete

While concrete varies greatly in its properties, satisfactory concrete for most purposes can be made with a wide range of aggregates by selection of materials and mix proportioning to provide concrete having required properties in both the freshly mixed and hardened state. The selection of the materials to be used in the concrete should be based on technical criteria, and moderated by economic considerations.

2.4.1 Cement

British standard (B.S.) No 12 has been produced to guide the purchase of this material in regard of the minimum qualities expected of the product and the tests that could be performed to satisfy that the cement meets the standard set up.

2.4.2 Aggregates

According to Leonhardt (1964) the mortar requirement of a concrete will be less as the coarse aggregate particle size is made larger. The particles of sand should not be smaller than necessary, as this will increase the total specific surface area to be wetted with cement paste, and consequently a wetter mix (giving a weaker concrete) would be required for any desired workability. As the sand in the mix becomes finner, a lower

percentage is required. An excessive content of fines has an adverse effect on the density of the concrete and increases its shrinkage because the water requirement of the mix increases.

2.4.3 Water

The least expensive constituent of concrete is water, It is none the less one of the more important of the materials in a concrete mix. It takes part in the chemical reaction of cement hydration. Dhir and Jackson (1984) observed that a concrete mix containing the minimum amount of water required for complete hydration of its cement, if it could be fully compacted, would develope the maximum attainable strength at any given age.

Mixing water for concrete should be reasonably clean and free from objectionable quantities of organic matter, slit, alkali or salts. Sulphate-bearing waters are likely to be harmful, and water contaminated by efluents from sewage works and from some industrial processes may contain deleterious materials. Water contaminated by organic impurities absorbed from peat deposits may also be unsuitable. There is no special test for determining at source the suitability of water for concrete, but generally water fit for drinking purposes will be suitable for concrete, and water from a mains supply should be used if available. Information on methods of testing the suitability of water for concrete is contained in BS 3148: 1980 tests for water for making concrete.

2.5 Testing of Concrete

Tests are often carried out in the two main states of concrete (freshly mixed and hardened states) in order to

appraise the properties of concrete. In the freshly mixed state, the property of interest is the workability of concrete while in the hardened state the main property of interest is the strength of concrete. Details of methods of testing concrete are described in BS 1881: 1970.

2.5.1 Workability of Concrete

The strength, appearance, permeability, and general serviceability of concrete is dependent on the effective placement and consolidation of freshly mixed concrete without undersirable voids and honey combing. Aggregate properties must be considered in proportioning concrete for adequate workability, changes in the aggregate grading or particle shape affect mixing water requirement and therefore the consistency of the concrete. Two tests most commonly used to access workability of Gap-graded concretes are the slump test and the vebe test. The slump test is easy to carry out and requires only simple apparatus. It is largely used for control purpose where the ingredients and proportioning of the mix remain unaltered and it may be used to ensure that there is no excess of water in the concrete. It is not generally believed, however, to give a true measure of workability.

Kar and Ray (1974) used the slump, Vebe, compaction factor and flow tests to assess the workability or consistency of their partially Gap-graded concrete mixes. Litvin and Pfeifer (1965) used the slump and vebe tests and found the standard slump test to be inadequate as a measure of the workability of such concretes (concretes with high proportion of coarse aggregate). The workability of this type of

concrete may be obtained with a vebe consistometer.

The vebe consistometer test is basically a remoulding test and therefore indicates a combination of both compactability and mobility of vibrated concrete. It gives a good reproduction of practical conditions such that a satisfactory vebe time not only indicates a suitable compactability but also, almost invariably at least an adequate mobility as well. The apparatus subjects the concrete to a slumping test on a vibrating table. The criterion of this test is the time in seconds required to consolidate the slump cone in 24cm. diameter cylindrical mass. A suitable vebe time for the conditions of placing and the compacting methods available can be obtained from Table 2.5. Details of method of testing the workability of concrete are described in BS 1881, Part 2: 1970 methods of testing fresh concrete.

2.5.2 Strength of Concrete

Dhir and Jackson (1984) defined the strength of concrete as the maximum load (stress) it can carry. As the strength of concrete increases its other properties usually improve and since the tests for strength, particularly in compression, are relatively simple to perform, concrete compressive strength is commonly used in the construction industry for the purpose of specification and quality control.

Compressive Strength: The compressive strength of concrete is taken as the maximum compressive load it can carry per unit area. Details of method of testing the compressive strength of concrete are described in BS 1881: Part 4: 1970 Methods of testing concrete for strength.

Table 2.5: Suggested mean values of compactability for different applications and equipment (obtained from Hughes, (1968))

Application	Vebe* sec.	Compacting factor*	Slump* in. mm.
Heavily-reinforced sections with light immersion vibrators. Simply-reinforced sections without vibration.	(3)	0.93	(1½ -4) (40-100)
Heavily-reinforced sections with immersion vibrators. Concrete suitable for pumping	(4)	0.91	(1-3) (25-75)
Reinforced sections with immersion vibrators.	6	(0.87)	(¾-2) (13-50)
Reinforced sections with heavy immersion vibrators. Road slabs with hand-operated machines.	8	(0.83)	(0-1) (0-25)
Mass concrete and other large sections with heavy immersion vibrators. Road slabs with power-operated machines.	12	(0.78)	-
Table vibration of heavy precast units, etc.	16	-	-
Heavily-vibrated or mechanically-compacted concrete in precast units, etc.	32	-	-
Table vibration of light precast units, etc.	24	-	-
Extremely intensive vibration, pressure may also be necessary	(40+)	-	-

*Values in brackets are the least reliable.

Tensile Strength: A number of test methods have been used to evaluate this property. BS 1881: Part 4 describes some of these methods.

In the direct test for tensile strength, the specimen is gripped at its ends and pulled apart in tension tensile strength is failure load divided by area.

In the splitting tension, test, a cylinder is loaded in compression on two diametrically opposite elements, failing in tension on the plane between the loaded elements. In the modulus of rupture test, a rectangular beam is loaded at the centre or third points and fails in bending, with the computed tensile stress at failure load called modulus of rupture.

In the splitting tension test, tensile strength is computed as:

$$Fs = \frac{2P}{\pi LD}$$

Where,

Fs = Splitting tensile stress, N/mm^2.

P = Total load at Failure, N.

L = Length of cylinder, mm.

D = Diameter of cylinder, mm.

2.5.3 Statistical Analysis of Tests Results

Dhir and Jackson (1988) affirmed that it is usual for sets of two control specimens to be made from each sample of concrete mix, one set being tested at 28 days and/or seven days or earlier in some cases. The result thus

obtained are analysed statistically to obtain premises for quality control.

It has been found by experiment that the strength of samples taken from a batch of material approximates to the normal distribution curve shown in Fig. 2.3.

Either the average strength or the minimum strength may be used in specifying the strength of a material. The average strength however, does not take account of the range of strengths in a batch. The distribution curve shows that it would not be realistic to specify a minimum strength because there is always the probability that some samples would fail to satisfy this.

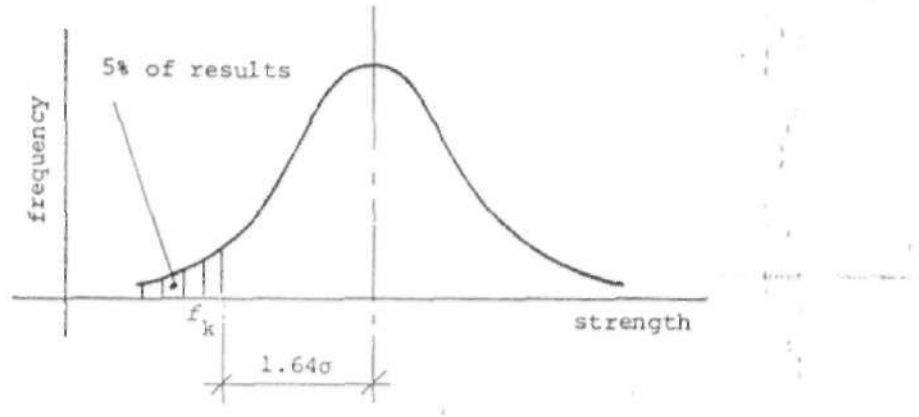


Fig. 2.3. Normal Distribution Curve.

Characteristic Strength: BS 8110 Part 1 (1985), defines characteristic strength as that value of the cube strength of concrete, fcu, the yeild or proof strength of reinforcement, fy, or the ultimate strength of a presetressing tendon, fpu, below which five per cent of all possible test results would be expected to fall.

It can be shown that this criterion is satisfied if $fk = \bar{X} - 1.64\sigma$ as shown in Fig. 2.3.

Where,

fk = Characteristic strength

x = The strength of a sample

$\bar{x}$ = Arithmetic mean of the sample strengths.

n = Number of samples

σ = The standard deviation = $\sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$

2.6 Gap-Graded Recycled Concrete

This review has revealed that quite a number of research workers have examined some of the basic properties of gap-graded concrete, and concrete made with recycled aggregates. There is sufficient evidence that old concrete can be processed into recycled aggregate using conventional equipment. There is also evidence that concrete strength and other properties may be improved by gap-grading.

The general differences in the physical properties of recycled concrete are the higher water absorption, higher drying shrinkage, lower modulus of elasticity and lower strength. There has been no evidence on the effect of grading on the strength and other characteristic of recycled concrete. If the claims of the advantages of gap-grading are true, it is expected that gap-grading of recycled concrete may redress some anomalies that are associated with the behaviour of recycled concrete.

Chapter 3

LABORATORY PROCEDURE

3.1 Materials

The following materials were used in the present work to produce recycled concrete: cement, Zaria crushed granite, crushed concrete aggregate, sand and water.

3.1.1 Cement

The cement used is an ordinary portland cement produced in Bauchi State of Nigeria. The brand is Ashaka Cement sold in paper bags containing 50kg each.

3.1.2 Coarse Aggregates

Two types of coarse aggregates were used in this research: Zaria crushed granite and crushed concrete aggregates. The Zaria crushed granite was obtained locally from the stockpiles of the Department of Building. It is produced in large quantities at several Quarries located within the Zaria environs. All the quantities of this material used were clean and free from deleterious substances. Concrete produced using the granite coarse aggregate was processed into aggregates passing 20mm sieve by sledge hammer and mechanical crushing and sizing.

All passing 20 mm sieve but retained on 10 mm sieve were used in this work. Selected physical properties of the aggregate were obtained from results of laboratory tests. Fig. 3.1 shows the grading curves of aggregates used in this work.

3.1.3 Sand

River sand dredged from riverbeds located within the Zaria environs was used in all the mixtures as fine aggregate. The sand used was clean free from silt and other deliterious substances.

The sand was regraded to comply with four pre-determined gradings which represent one continuous and three gap-gradings of the concrete mixtures of this work.

3.1.4 Water

Tap water was used in all the mixtures of this research. This meets the minimum requirement normally specified for concrete work.

3.2 Mixtures

One round of a single concrete mixture was made out of which eighty cubes and eighty cylinders of concrete were obtained. These cubes and cylinders of concrete were processed into aggregates for recycled concrete after ninety days curing at normal temperature under water. One round each of four concrete mixtures was made from the recycled concrete aggregates. The mixtures are identified in Table 3.1.

Table 3.1: Mixture Characteristics

Mix No	Cement	Coarse Aggregate		Fine Aggregate		Aggregate/ Cement ratio	Water/ cement ratio	Grading
		Type	Max. Size (mm)	Type	Content Per cent			
1	Ordinary Portland	Zaria crushed Granite	20.0	River sand	30	9	0.7	Continuous
2	Ordinary Portland	Recycled Concrete	20.0	River sand	30	9	0.7	Continuous
3	Ordinary Portland	Recycled Concrete	20.0	River sand	30	9	0.7	Gap
4	Ordinary Portland	Recycled Concrete	20.0	River sand	25	9	0.7	Gap
5	Ordinary Portland	Recycled Concrete	20.0	River sand	20	9	0.7	Gap

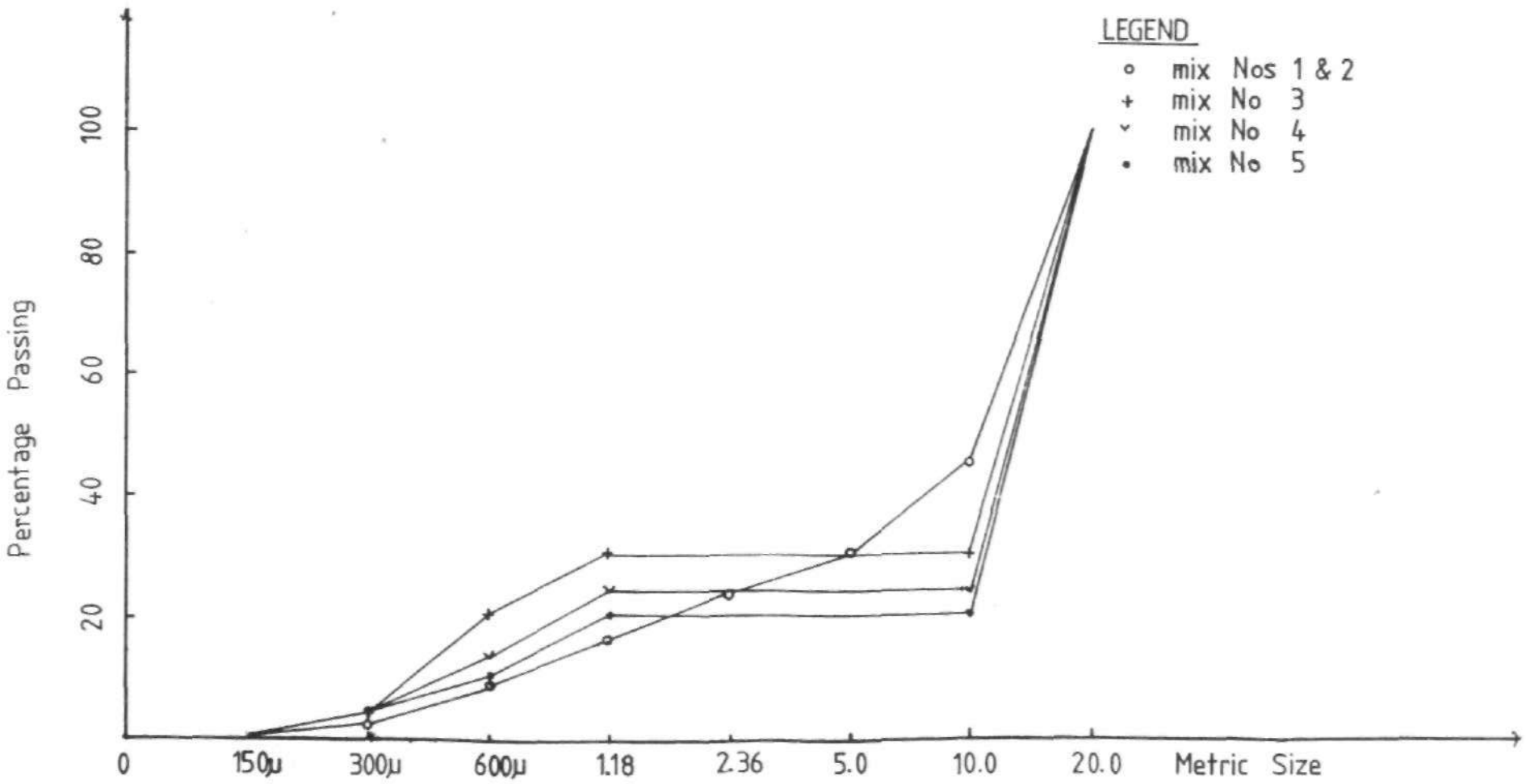


Fig: 3.1 Grading Curves of Aggregates [20mm maximum size]

Constant water-cement and Aggregate-cement ratios were maintained in all mixtures. Also a maximum aggregate size of 20 mm was maintained in all mixtures. These helped to reduce the number of variables that could have influenced the results of tests.

Mixture 2 was a repeat of Mixture 1 to obtain a basis of comparison for the compressive strength of gap graded recycled concrete.

Mixture 4 and 5 were made to evaluate the effect of decreasing sand content on the compressive strength of gap graded recycled concrete.

3.2.1 Mix Proportions

The following calculations were made in order to determine the amount of the various materials required for each mix in respect of both the original and recycled concrete.

Mix No 1: The mix proportions are 1 part of cement to

$9 \times \frac{30}{100}$ = 2.7 parts of sand to

$9 \times \frac{70}{100}$ = 6.3 parts of crushed granite

OR 1:2.7:6.3/0.70

Assuming the specific gravity of cement to be 3.15, that of coarse aggregate 2.63, and of fine aggregate 2.75, the cement content C, in Kg/m^3 may be obtained from the expression.

$$\frac{W}{1000} + \frac{C}{1000Pc} + \frac{A1}{1000\ P_1} + \frac{A_2}{1000P_2} = 1$$

Where

W = Water content

C = Cement content

A_1 = Fine aggregate content

A_2 = Coarse aggregate content

P_1 = Apparent specific gravity of fine aggregate

P_2 = Apparent specific gravity of coarse aggregate

Pc = Apparent specific gravity of cement

$$\frac{0.7C}{1000} + \frac{C}{1000 \times 3.15} + \frac{2.7C}{1000 \times 2.75} + \frac{6.3C}{1000 \times 2.63} = 1$$

$$2.205 + C + 3.09C + 7.545C = 3150$$

$$C = 227.55 \text{ kg/m}^3$$

(a) Volume of 1 cube = $(0.15)^3$ = $0.003375 \blacksquare^3$

Volume of 80 cubes = $0.27m^3$

Quantity of cement required for

80 cubes of concrete = 0.27 x 227.55 = 61.50kg

Add 10% of waste = 67.6kg

Natural sand = 2.7 x 67.6 = 182.50 kg

Crushed Granite = 6.3 x 6.7 = 425.90 kg.

Water = 0.7 x 67.6 = 47.30 kg

(b) Volume of 1 cylinder = 0.00530 m^3

Volume of 80 cylinders = 0.424 m^3

Quantity of cement required for

80 cylinders = 0.424 x 227.55 = 96.50 kg

Add 10% for waste = 106.20 kg

Natural Sand = 2.7 x 106.2 = 286.70 kg

Crushed Granite = 6.3 x 106.2 = 699.10 kg

Water = 0.7 x 106.2 = 74.35 kg

Mix No 2: The mix proportions are 1:2.7:6.3/0.70

$$\frac{0.7C}{1000} + \frac{C}{1000 \times 3.15} + \frac{2.7C}{1000 \times 2.75} + \frac{6.3C}{1000 \times 2.59} = 1$$

$$2.205C + C + 3.093C + 7.662C = 3150$$

$$C = 225.64 \text{ kg/m}^3$$

(a) Volume of 1 cube = $0.003375 m^3$ (b) Volume of 1 cylinder = $.00053 m^3$

Volume of 20 cubes = $0.0675 m^3$ 20 cylinders = $0.106 m^3$

Required Quantity of cement for

(a) 20 cubes = 15.20kg (b) 20 cylinders = 23.90kg
Add 10% for waste = 16.70 kg = 26.30 kg

Quantities of materials for:		20 cubes	20 cylinders
Cement	=	16.7 kg	26.3 kg
Natural sand	=	45.10 kg	71.0 kg
Recycled Coarse Aggregate		105.2 kg	165.7 kg
Water	=	11.7 kg	18.4 kg

Mix No 3: The mix proportions are: 1:2.7:6.3/0.70.

Quantities of materials for:		20 cubes	20 cylinders
Cement	=	16.7 kg	26.3 kg
Natural Sand	=	45.10 kg	71.0 kg
Recycled Coarse Aggregate	=	105.20 kg	165.7 kg
Water	=	11.70 kg	18.4 kg

Mix No 4: The mix proportions are: 1:2.25:6.75/0.7

$$\frac{0.7C}{1000} + \frac{C}{1000 \times 3.15} + \frac{2.25C}{1000 \times 2.75} + \frac{6.75C}{1000 \times 2.59} = 1$$

$$2.505C + C + 2.577C + 8.209C = 3150$$

$$C = 220.42 \text{ kg/m}^3$$

(a) Volume of 20 cubes = $0.0675 m^3$ (b) Volume of 20 cylinders = $0.106 m^3$

Required quantity of cement for

(a) 20 cubes = 14.9 kg (b) 20 cylinders = 23.4 kg
Add 10% for waste = 16.4 kg = 25.70 kg

Quantities of Materials for:	20 cubes	20 cylinders
Cement	16.4 kg	25.7 kg
Natural Sand	36.9 kg	57.8 kg
Recycled Coarse Aggregate	110.7 kg	173.5 kg
Water	11.5 kg	18.0 kg

Mix No 5: The mix proportions are 1:1.8:7.20/0.7.

$$\frac{0.7C}{1000} + \frac{C}{1000 \times 3.15} + \frac{1.8C}{1000 \times 2.75} + \frac{7.2C}{1000 \times 2.59} = 1$$

$$2.505C + C + 2.062C + 8.757C = 3150$$

$$C = 220.0 \text{ kg/m}^3$$

Required Quantities of cement for:

	(a) 20 cube	(b) 20 cylinders
	16.3 kg	25.65 kg
Natural sand	29.3 kg	46.2 kg
Recycled Coarse Aggregate	117.4 kg	184.7 kg
Water	11.4 kg	18.0 kg

3.2.2. Production of Concrete

All the concretes used were weigh batched and mixed using a revolving and tilting drum type of mixer. All concretes were well mixed according to predetermined gradation of aggregates See Fig 3.1.

Concretes were cast in clean and oiled cubic and cylindrical moulds of sizes 150 mm x 150 mm and 150 mm (diameter) x 300mm respectively. Casting of concrete in each mould was done in three layers and thorough compaction was achieved using, a table vibrator.



Plate II. Screening and sizing of Aggregate for concrete



Concrete cubes and cylinders were removed from moulds 24 hours after cast, labelled and cured under water at room temperature till the day of tests.

After 90 days of cast and curing, the original granite concrete was processed into aggregates passing a 20.0 mm sieve by sledge hammer and mechanical crushing and sizing. The fines of the recycled concrete aggregate were disregarded.

All concrete cubes and cylinders were weighed to determine the bulk density.

$$\text{Bulk density} = \frac{\text{Mass (Kg)}}{\text{Volume } (m^3)}$$

3.3 Tests

Some of the tests undertaken in the laboratory in respect of this work are mentioned in the foregoing.

3.3.1 Absorption

The determination of the absorption of a new aggregate is essential because the rate of absorption of aggregates affects the water content of a mix.

The absorption of an aggregate is determined by measuring the increase in weight of an oven dry sample, after 24 hours immersion in water (the surface moisture being removed). The ratio of the increase in weight to the weight of the dry sample expressed as a percentage gives the absorption of the sample.

The absorption per cent for the coarse aggregates used in this work are stated in the chapter four of this thesis.

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3.3.2 Specific Gravity

The determination of specific gravity is described in BS 812: samples of the aggregate were immersed in water, stirred to remove air bubbles, and allowed to stand for 24 hours. The samples were then removed and fanned to a surface dry condition and weighed.

The Pycnometer is the vessel usually specified to be used in the determination of specific gravity test. It is usually a one-litre jar with a water tight metal conical screwtop having a small hole at the apex. The pycnometer can be filled with water so as to contain precisely the same volume everytime.

The calculation is based on the followings:

C = weight of the saturated and surface dry sample.

B = weight of vessel full of water

A = weight of the vessel with the sample topped up with water

B - (A-C) = weight of the water occupying the same volume as the sample of aggregate.

$$\text{Specific Gravity} = \frac{C}{B-A+C}$$

The results of specific gravity test are given in chapter four of this thesis.

3.3.3 Slump Test

The test was frequently mentioned in previous works on gap graded concrete. It was found to be inadequate for measuring the workability but suitable for excercising control of mixture characteristics. The vebe test was found to be a superior method of measuring workability of dry mixtures but the apparatus wasnot available in the laboratory at the time of testing and as such could not be used.

The detailed description of the procedure for carrying out this test is contained in B S 1881. The mould for the slump test is a frustum of a cone, 305 mm high. An inspection of the internal surface of the conical apparatus is first made to ensure that it is clean, dry and free from particulate attachments. It is placed on a smooth surface base plate made of steel or polyvinyl chloride with the smaller opening at the top. It is then filled with representative sample of concrete in three layers, each layer being tamped 25 times with 16 mm diameter steel rod; The top level is struck off by means of a screeding and rolling motion of the tamping rod. The mould is carefully raised in a vertical direction and the slump measured. If shear or collapse slump occur the test is repeated.

The slump obtained is mentioned in chapter four of this thesis.

3.3.4 Compression Test

The compressive strength test was carried out as specified in B S 1881: Part 4: 1970 methods of testing concrete for strength.

The crushing loads of cubes specimens were obtained from the compression machine after the crushing of each cube. Cubes for Mix no 1 were crushed after 28 and 90 days curing. Cubes for mix no 2 to 5 were crushed after 7, 28 and 90 days curing. A total number of 180 cubes of size 150 mm x 150 mm x 150 mm were crushed all together.



Plate IV Cube Crushing Test



Plate V Cylinder Splitting Test

The compressive strength is determined by dividing the failure load by the surface area of the cube.

i.e. compressive strength = $\frac{\text{Load at Failure (N)}}{\text{Surface area (mm}^2\text{)}}$

A summary of the compressive strength test results for all the mixtures are shown in table 4.3.

A chief Technologist and his team of two assistants were directly involved in the operation of the compression machine, ensuring that all precautions necessary to give the best results were strictly complied with.

The details of results obtained from compressive strength tests are shown in Appendix I.

3.3.5 Tensile Strength

Tensile strenth test was carried out in accordance with specifications of B S 1881: Part 4: 1970 Methods of testing concrete for strength.

The cylinder splitting test method was adopted for the purpose of this work. In this test, a concrete cylinder , is placed with the axis horizontal between the platens, of a testing machine, and the load is applied and increased until failure by splitting along the vertical diameter take place. Narrow strips of particle board of about 7 mm thick by 35 mm wide used as packing material were inter posed between the cylinder and the platens.

The strength is expressed in terms of $\frac{2P}{\pi LD}$

Table 4.4 shows the summary of tests results. Other details are in appendix II.



Plate VI Centralizing the narrow strip of particle board between the cylinder and the platen before test.



Plate VII Observing and recording of failure loads.

Chapter 4

TEST RESULTS AND DISCUSSION

The summaries of the results of the various tests performed are presented below. The detailed results of the major tests (Tensile and compressive strength tests) are to be found in the appendices.

4.1 Selected Physical Properties of Aggregates

Table 4.1 shows some physical properties of aggregates used in the concrete production. The recycled concrete had an average absorption of 4.7%, and 2.59 apparent specific gravity. As previously found by Buck (1977) the specific gravity of aggregate made from recycled concrete tends to be lower and its absorption tends to be higher than these properties of conventional aggregates. These differences have not caused any problems in the use of recycled concrete as aggregate.

4.2 Slump

The slumps and cement contents of the five mixtures are shown in table 4.2. The cement content of the Control Mixture 1 was 227.55kg/m^3, mix 3, 4 and 5 had slightly lower slump than desired. The cement content of these mixtures can be increased to increase workability.

4.3 Compressive Strength

The average compressive strengths of each mixture for ages of from 7 to 90 days are shown in Table 4.3 and Fig. 4.1. The comprehensive details of these results are to be found in Appendix I.

Table 4.1: Physical Properties of Aggregates

	Zaria Crushed Granite	River Sand	Crushed Concrete (20.0-10.0mm)
Absorption %	0.36	0.65	4.7
Specific Gravity	2.63	2.75	2.59

Table 4.2: Selected Physical Properties of Five Concrete Mixtures

Mixture		Slump, mm	Cement Content kg/m^3
Mix 1:	Zaria crushed granite and fine sand	10 - 20	227.55
Mix 2:	Continuously graded Recycled concrete and fine sand	0 - 10	225.64
Mix 3:	Gap graded Recycled concrete and fine sand	0 - 10	225.64
Mix 4:	Gap graded Recycled concrete and fine sand	3 - 10	220.42
Mix 5:	Gap graded Recycled concrete and fine sand	5 - 10	220.0

Previous works on recycled concrete was confined to determining the physical properties, compressive strength, and stress-strain data for continuously graded mixtures. Conclusions arrived at in these works and those reached in this report of gap-graded mixtures where comparable, are in good agreement.

It has already been mentioned that the percentage of fines has a limiting effect on the compressive strength of concrete produced using recycled coarse and fine aggregates in a mixture. In this case where river sand was used as fine aggregate a reduction of fine aggregates content of the control mix by five percent did not show any appreciable effect on the compressive strength. A further reduction by five percent in mix 5 caused a decrease of about 36% in compressive strength.

The intent of mixtures 1 and 2 was to determine whether mix 2 having the same mix characteristics as mixture 1 but containing a recycled concrete aggregate produced using the same proportions as in mixture 1 will show any appreciable improvement over previous reports of this nature. The compressive strength for mix 2 showed about 25% decrease in strength as compared to mix 1.

It was intended that mixture 3 be a remake of mixture 2 with gaps introduced in the aggregate grading as the only

variable. The effect of the gap grading of mixture 3 was to increase its compressive strength about $4N/mm^2$ over that of mixture 2 about 25% increase in compressive strength. Further comparison of the compressive strength of mixture 3 with that of mixtures 4 and 5 involves the variable of fine sand content. However, in both cases the compressive strength of mixture 3 was higher than that of the other mixtures.

Fig. 4.2 shows the relationship between compressive strength and wet density. The results obtained confirms the fact that when all other things are equal compressive strength is proportional to density of concrete. From Tables 4.2 and 4.3 it may be adduced that high cement content is not necessarily a guarantee for high strength. Cement content coupled with improved grading should improve strength.

The cement content for mixture 4 is 220.42 Kg/m^3. This value is about 7 kg/m^3 less than the value for mixture 1, 5 kg/m^3 less than for mixtures 2 and 3, and about the same for mixture 5. From the computed compressive strength results shown in Table 4.3, it appears that mixture 4 would produce a more economical concrete than the other mixtures, especially where large volumes of concrete is required.

Table 4.3: Summary of Tests results for Compressive Strength

Mix No	No of specimens Tested	Mix Proportion (by weight)	Cube Compressive Strength (N/mm^2)			
			Average Density Kg/m^3	7days	28days	90days
1	5	1:2.7:6.3/0.7	2409.0	nd	19.6	21.9
2	5	1:2.7:6.3/0.7	2104.0	11.6	13.0	16.4
3	5	1:2.7:6.3/0.7	2140.0	12.3	14.4	20.1
4	5	1:2.25:6.75/0.7	2162.0	11.3	13.8	19.9
5	5	1:1.8:7.2/0.7	1999.0	8.4	9.9	12.9

Table 4.4: Summary of tests results for tensile strength

Mix No	No. of Specimens Tested	Mix Proportion (by weight)	Cylinder Splitting Tensile Strength N/mm^2		
			Average Density kg/m^3	28 days	90 days
1	5	1:2.7:6.3/0.7	2453.0	2.4	2.7
2	5	1:2.7:6.3/0.7	2152.0	1.8	2.1
3	5	1:2.7:6.3/0.7	2163.0	1.8	2.4
4	5	1:2.25:6.75/0.7	2177.0	1.7	2.2
5	5	1:1.8:7.2/0.7	2097.0	1.4	1.6

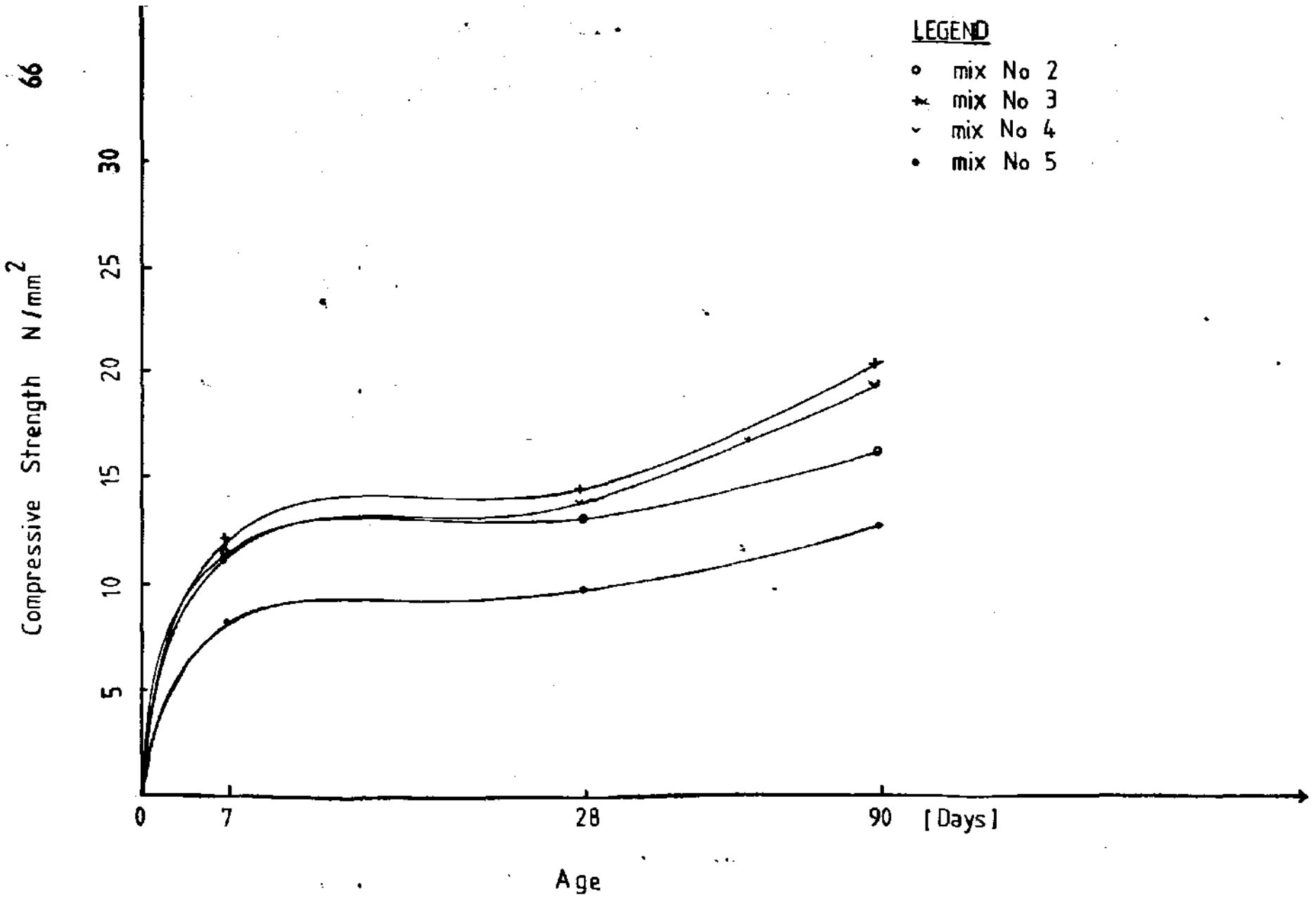


Fig: 4.1 Relation Between Compressive Strength and Age

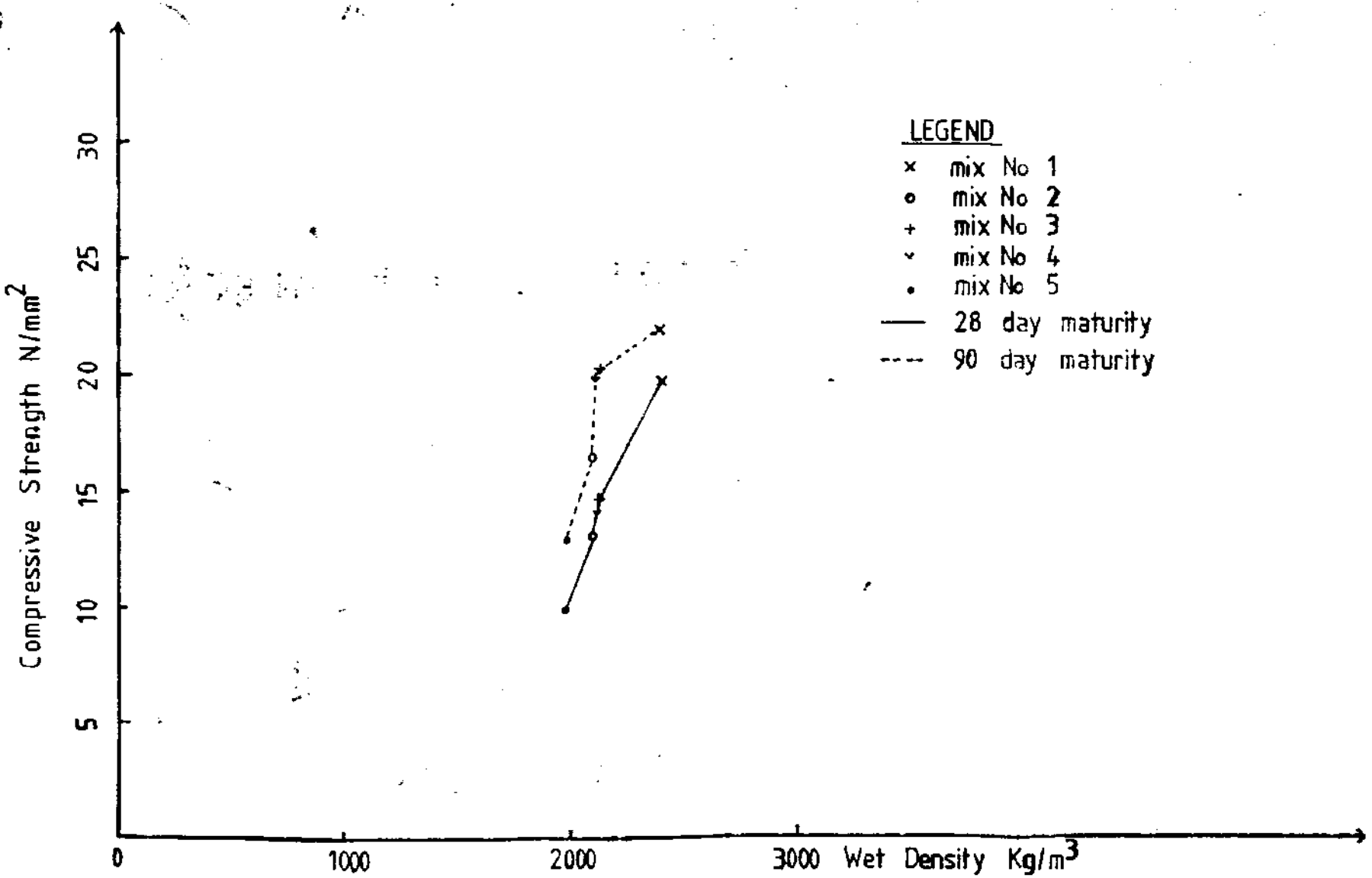


Fig: 4. 2 Relation Between Compressive Strength and Wet Density

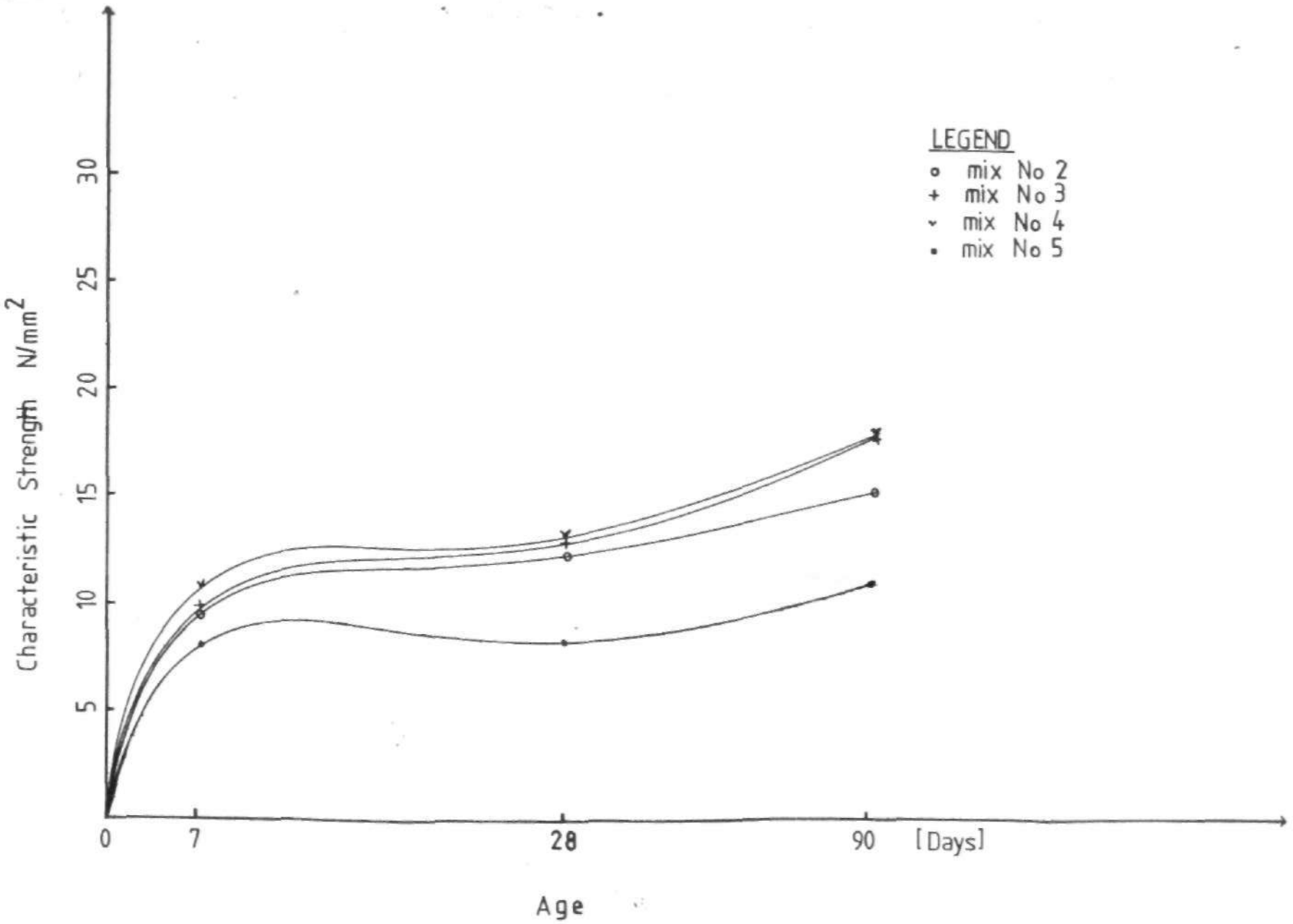


Fig: 4.3 Relation Between Characteristic Strength and Age.

Mixture 2, a continuously graded recycled concrete gained about 66% of the compressive strength of the control mixture 1 in 28 days and 75% in 90 days; Mixture 3, a gap graded recycled concrete gained about 73% of the compressive strength of the control Mixture 1 in 28 days and 92% in 90 days. Indicating that gap graded recycled concrete mixtures have higher rates of strength development when compared with continuously graded mixtures of equivalent water cement ratio or mixture characteristics.

4.4 Tensile Strength

The average tensile strengths of each mixture for ages of from 28 to 90 days are shown in Table 4.4 Other details of these results are to be found in appendix II.

It is apparent that the tensile strength of recycled concrete is lower than that of conventional concrete of the same mixture characteristics. It is also evident that the tensile strength of gap graded recycled concrete is higher than continuously graded recycled concrete of equivalent mixture characteristics.

The tensile strength of concrete is usually very low and the results obtained in this work tends to support this fact and falls within the acceptable range of 5.0 to 12.5% of the cube crushing strength.

4.5 Characteristic Strength

The characteristic crushing strength f_k may be expressed in terms of the standard deviation σ by the relationship:

$$Fk = \bar{x} - 1.64\sigma$$

Where

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$$

x = the strength of a sample

$\bar{x}$ = arithmetic mean of the sample strengths.

n = number of samples.

Values of characteristic strengths estimated for ranges of crushing strengths results obtained are shown in Table 4.5. An attempt to apply the same analysis on values of splitting strengths results obtained is shown on Table 4.6.

From the results computed for compressive strengths and shown in Table 4.5, it appears that the characteristic strength of mixture 4 was higher than that of the other recycled mixtures.

4.6 Graphs

Graphs illustrating the relationships between various parameters of concrete properties have been shown in Figs 4.1 to 4.3. It would be observed that the curves in Figs 4.1 and 4.3 show slight deviations from standard curves of concrete strength development with age as shown previously in Fig 2.2 (Page 24). The reason for this is probably due to the low compressive strength values obtained for all specimens at 28 days maturity. The specimens were cast during the first week of December, 1990, at that time the weather was still relatively warm. About a week later the cold harmattan weather set in, became severe in the early weeks of January and remained cold throughout the months of January and most of february. The weather changed again from cold to warm during the last week of February and temperature continued to rise slowly up to the raining season.

The 7th day strengths were obtained in December while the temperature was still warm and contributive to the high rate of strength development recorded. The 28th day strengths were obtained in mid January after the temperature had fallen and the weather became severely cold for over a period of two weeks, this drop in temperature may have retarded the rate of strength development. The 90th day strengths were obtained in early March after the transition from the cold harmattan to the warm weather proceeding the raining seasons. These variations in temperatures during the period of curing and testing may have been the root cause of the slight deviations observed in Figs 4.1 and 4.3 when compared to standard curves of this nature.

Temperature readings of the weather changes were not taken during the period of testing.

Table 4.5: Summary of Statistical Analysis of Strength Of Concrete Cubes

Mix	Age Days	Mean Strength N/mm^2 $(\bar{x})$	Standard Deviation σ	1.64σ	Characteristic Strength N/mm^2
1	28	19.56	1.750	2.87	16.69
	90	21.86	1.350	2.21	19.65
2	7	11.64	1.22	2.0	9.64
	28	13.04	0.560	0.92	12.12
	90	16.36	0.569	0.93	15.43
3	7	12.08	0.790	1.29	10.79
	28	14.40	0.940	1.54	12.86
	90	20.10	1.445	2.37	17.73
4	7	11.30	0.917	1.50	9.8
	28	13.76	0.450	0.74	13.02
	90	19.90	0.946	1.55	18.35
5	7	8.50	0.224	0.37	8.13
	28	9.88	1.010	1.66	8.22
	90	12.30	0.784	1.29	11.01

Table 4.6: Summary of Statistical Analysis of Strength of Concrete Cylinders

Mix	Age Days	Mean Strength $(\bar{x})$ N/mm²	Standard Deviation σ	1.64σ	$\bar{x} - 1.64\sigma$
1	28	2.36	0.261	0.43	1.93
	90	2.70	0.469	0.77	1.93
2	28	1.80	0.274	0.45	1.35
	90	2.12	0.164	0.27	1.85
3	28	1.84	0.167	0.27	1.57
	90	2.36	0.251	0.41	1.95
4	28	1.72	0.268	0.44	1.28
	90	2.16	0.416	0.68	1.48
5	28	1.44	0.230	0.38	1.06
	90	1.58	0.342	0.56	1.02

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on this work the following conclusions appear valid:

a. Gap-graded recycled concrete, though of a relatively stiffer and drier mix, can be placed and finished satisfactorily using mechanical vibrators to ensure that full compaction is achieved.

b. The use of gap-graded recycled concrete at given water-cement ratio and aggregate-cement ratio required no additional cement than that for continuously graded recycled mixtures.

c. The use of low-strength recycled concrete as aggregate need not be detrimental to the compressive strength of concrete mixtures that contain this aggregate.

d. The use of gap-graded aggregates in recycled concrete production is effective in increasing the strengths of concrete mixtures that contain fine sand as fine aggregate and 25 to 30% sand content.

e. With regards to 90 days compressive strength results obtained, it could be shown that the tendency of concrete containing recycled concrete as aggregate to be at lower strength for equal water-cement ratio than controls made using similar aggregate

can be overcome with no increase in cement content or sacrifice of workability, by introducing gaps in the grading of the mixtures.

f. The data presented here indicate that the compressive and tensile strengths of a gap-graded recycled concrete are higher than continuously graded recycled concrete of similar mixture characteristics.

g. Overall consideration of present data and that found in the literature review indicates that gap grading of recycled concrete is a practical and economical procedure.

5.2 Recommendations

Within the premises of this investigation, it is recommended that:

a. Recycled concrete may be gap-graded in order to improve its compressive strength.

b. Gap-graded recycled concrete can be used for all construction where continuously graded recycled concrete has been used up to now.

c. Investigations should be carried out on ways of reducing the cement content without sacrificing the compressive strength of gap-graded recycled concrete. This may be possible by (i) considering the specific surface area of aggregates applied to mix proportioning, (ii) employing the optimum

mix design method proposed by Shu-t'ien Li and V Ramakrishnan (See Appendix IV).

d. Further research work should be carried out on other properties of gap-graded recycled concrete; such as on modulus of elasticity, anchorage bond strength, shear, creep and shrinkage properties as soon as necessary equipment are available in the laboratory.

e. Barriers to the use of recycled concrete such as failure to mention it as a category of materials along with gravel, crushed stone, etc should be removed.

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APPENDIX 1

RESULTS OF COMPRESSIVE TESTS

Table 5.1 : 28 - Day compression test for Mix No 1

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
1.	28	A11	8.1	2400.0	480.0	21.33
		A12	8.3	2459.0	480.0	21.33
		A13	8.1	2400.0	440.0	19.56
		A14	8.0	2370.0	400.0	17.78
		A15	8.1	2400.0	400.0	17.78
		Average	8.1	2406.0	440.0	19.60

Table 5.2 : 90 - Day Compression test for Mix No 1

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
1	90	A21	8.1	2400.0	480.0	21.33
		A22	8.2	2430.0	540.0	24.00
		A23	8.0	2370.0	460.0	20.44
		A24	8.2	2430.0	480.0	21.33
		A25	8.2	2430.0	500.0	22.22
		Average	8.1	2412.0	492.0	21.90

Table 5.3 : 7-day compression test for mix No 2

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
2	7	A31	7.2	2133.0	280.0	12.4
		A32	7.1	2104.0	270.0	12.0
		A33	7.1	2104.0	220.0	9.8
		A34	7.0	2074.0	250.0	11.1
		A35	7.2	2133.0	290.0	12.9
		Average	7.1	2110.0	262.0	11.64

Table 5.4: 28 - day compression test for mix No 2

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
2	28	A41	7.2	2133.0	320.0	14.2
		A42	7.0	2074.0	290.0	12.9
		A43	7.1	2104.0	300.0	13.3
		A44	7.1	2104.0	280.0	12.4
		A45	7.1	2104.0	280.0	12.4
		Average	7.1	2104.0	294.0	13.0

Table 5.5 : 7 - day Compression test for mix No 3

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
3	7	X31	7.0	2074.0	250.0	11.1
		X32	7.1	2104.0	270.0	12.0
		X33	7.1	2104.0	270.0	12.0
		X34	7.3	2163.0	300.0	13.3
		X35	7.1	2104.0	300.0	12.0
		Average	7.10	2110.0	278.0	12.08

Table 5.6 : 28 day Compression test for mix No 3

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGTH KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
3	28	X26	7.4	2193.0	340.0	15.1
		X27	7.3	2163.0	350.0	15.6
		X28	7.1	2104.0	320.0	14.2
		X29	7.0	2074.0	300.0	13.3
		X20	7.0	2074.0	310.0	13.8
		Average	7.2	2122.0	324.0	14.4

Table 5.7 : 7 - day Compression test for Mix No 4

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGTH KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
4	7	Y31	7.0	2104.0	250.0	11.1
		Y32	6.9	2044.0	250.0	11.1
		Y33	7.0	2074.0	240.0	10.7
		Y34	7.4	2193.0	290.0	12.9
		Y35	7.1	2104.0	240.0	10.7
		Average	7.10	2104.0	254.0	11.3

Table 5.8 : 28 - day Compression test for mix No 4

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGTH KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
4	28	Y36	7.1	2104.0	320.0	14.2
		Y37	7.2	2133.0	300.0	13.3
		Y38	7.1	2104.0	300.0	13.3
		Y39	7.0	2074.0	320.0	14.2
		Y30	7.2	2133.0	310.0	13.8
		Average	7.10	2110.0	310.0	13.8

Table 5.9 : 7 - day Compression test for mix No 5

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGTH KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
5	7	Z21	6.4	1896.0	190.0	8.4
		Z22	6.5	1926.0	200.0	8.9
		Z23	6.5	1926.0	190.0	8.4
		Z24	6.7	1985.0	180.0	8.4
		Z25	6.7	1985.0	180.0	8.4
		Average	6.6	1944.0	190.0	8.5

Table 5.11 : 28 day Compression test for Mix No 5

MIX NO	AGE OF SPECIMEN (DAY)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRES-SIVE STRENGTH N/mm^2
5	28	Z26	6.4	1896.0	200.0	8.9
		Z27	6.8	2015.0	240.0	10.7
		Z28	6.8	2015.0	220.0	9.8
		Z29	6.7	1985.0	200.0	8.9
		Z20	6.9	2044.0	250.0	11.1
		Average	6.7	1991.0	222.0	9.9

Table 5.12 : 90 - day Compression test for Mix No 2

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
2	90	A51	7.3	2163.0	380.0	16.9
		A52	7.1	2104.0	360.0	16.0
		A53	7.0	2074.0	370.0	16.4
		A54	7.0	2074.0	350.0	15.6
		A55	7.0	2074.0	380.0	16.9
		Average	7.1	2098.0	368.0	16.4

Table 5.13: 90 - day Compression test for mix No 3

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
3	90	X21	7.2	2133.0	430.0	19.1
		X22	7.6	2252.0	490.0	21.8
		X23	7.3	2163.0	430.0	19.1
		X24	7.6	2252.0	470.0	20.9
		X25	7.2	2133.0	440.0	19.6
		Average	7.4	2187.0	452.0	20.1

Table 5.14 : 90 - day Compression test for mix No 4

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
4	90	Y21	7.4	2193.0	430.0	19.1
		Y22	7.3	2163.0	430.0	19.1
		Y23	7.3	2163.0	440.0	19.6
		Y24	7.3	2163.0	460.0	20.4
		Y25	7.5	2222.0	480.0	21.3
		Average	7.4	2181.0	448.0	19.9

Table 5.15 : 90 - day Compression test for mix No 5

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX CRUSH-ING LOAD KN	COMPRE-SSIVE STRENGTH N/mm^2
5	90	Z31	7.3	2163.0	300.0	13.3
		Z32	7.0	2074.0	280.0	12.4
		Z33	6.9	2044.0	280.0	12.4
		Z34	6.6	1955.0	250.0	11.1
		Z35	7.0	2074.0	280.0	12.3
		Average	7.0	2062.0	278.0	12.3

APPENDIX II

RESULTS OF TENSILE STRENGTH TESTS

Table 6.1 : 28 - day Cylinder Splitting test for mix No 1

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH K/mm^2
1	28	B10	13.0	2452.0	160.0	2.3
		B11	13.0	2452.0	160.0	2.3
		B12	12.6	2378.0	150.0	2.1
		B13	13.0	2452.0	160.0	2.3
		B14	12.8	2414.0	200.0	2.8
		Average	12.9	2430.0	160.0	2.4

Table 6.2: 90 - day Cylinder Splitting test for mix No 1

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH K/mm^2
1	90	B15	13.3	2509.0	240.0	3.4
		B16	13.0	2452.0	150.0	2.1
		B17	12.9	2433.0	180.0	2.6
		B18	13.2	2490.0	200.0	2.8
		B19	13.2	2490.0	180.0	2.6
		Average	13.1	2475.0	190.0	2.7

Table 6.3 : 28 - day Cylinder Splitting test for Mix No 2

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH K/mm^2
2	28	B20	11.6	2188.0	140.0	2.0
		B21	11.3	2131.0	120.0	1.7
		B22	11.6	2188.0	150.0	2.1
		B23	11.5	2169.0	100.0	1.4
		B24	11.7	2207.0	130.0	1.8
		Average	11.5	2177.0	128.0	1.8

Table 6.4: 90 - day Cylinder Splitting test for mix No 2

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH K/mm^2
2	90	B25	10.9	2056.0	140.0	2.0
		B26	11.3	2131.0	160.0	2.3
		B27	11.4	2150.0	160.0	2.3
		B28	11.4	2150.0	140.0	2.0
		B29	11.4	2150.0	140.0	2.0
		Average	11.3	2127.0	148.0	2.1

Table 6.5 : 28 - day Cylinder Splitting test for mix No 3

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
3	28	X10	11.5	2169.0	140.0	2.0
		X11	11.7	2207.0	130.0	1.8
		X12	11.7	2207.0	130.0	1.8
		X13	11.5	2169.0	110.0	1.6
		X14	11.8	2037.0	140.0	2.0
		Average	11.2	2158.0	130.0	1.8

Table 6.6: 90 - day Cylinder Splitting test for mix No 3

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
3	90	X15	11.4	2150.0	180.0	2.6
		X16	11.5	2169.0	160.0	2.3
		X17	11.4	2150.0	140.0	2.0
		X18	11.7	2207.0	180.0	2.6
		X19	11.5	2169.0	160.0	2.3
		Average	11.5	2169.0	164.0	2.4

Table 6.7 : 28 - day Cylinder Splitting test for Mix No 4

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
4	28	Y10	11.6	2188.0	140.0	2.0
		Y11	11.3	2131.0	140.0	2.0
		Y12	11.8	2226.0	110.0	1.6
		Y13	11.8	2226.0	100.0	1.4
		Y14	11.6	2188.0	110.0	1.6
		Average	11.6	2192.0	120.0	1.7

Table 6.8 : 19 - day Cylinder Splitting test for Mix no 4

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
4	90	Y15	11.8	2226.0	140.0	2.0
		Y16	11.1	2094.0	160.0	2.3
		Y17	11.9	2245.0	200.0	2.8
		Y18	11.4	2150.0	140.0	2.0
		Y19	11.1	2094.0	120.0	1.7
		Average	11.4	2162.0	152.0	2.2

Table 6.9: 28 - day Cylinder Splitting test for mix No 4

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
5	28	Z10	11.1	2094.0	120.0	1.7
		Z11	11.3	2131.0	110.0	1.6
		Z12	11.1	2094.0	80.0	1.1
		Z13	10.3	1943.0	100.0	1.4
		Z14	11.0	2075.0	100.0	1.4
		Average	11.0	2067.0	102.0	1.4

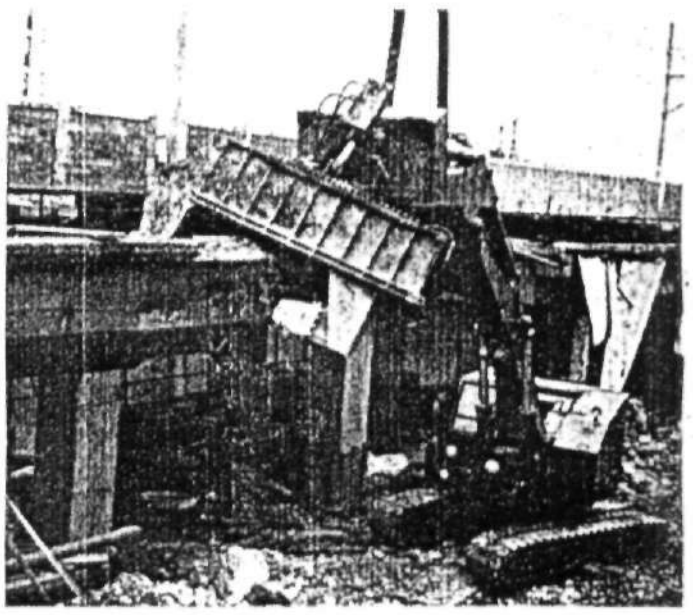
Table 6.11 : 90 - day Cylinder Splitting test for Mix No 5

MIX NO	AGE OF SPECIMEN (DAYS)	MARK ON SPECI-MEN	WEIGHT KG	DENSITY KG/m^3	MAX SPLITT-ING LOAD KN	TENSILE STRENGTH N/mm^2
5	90	Z15	10.9	2056.0	120.0	1.7
		Z16	11.4	2150.0	140.0	2.0
		Z17	11.3	2131.0	80.0	1.1
		Z18	11.4	2150.0	120.0	1.7
		Z19	11.4	2150.0	100.0	1.4
		Average	11.3	2127.0	112.0	1.6

APPENDIX III (Obtained from Construction and Equipment, July 1974)

Long-reaching, adjustable hydraulic breaker machines demolish concrete structures

Four hydraulic breaker machines designed for noiseless, shockless, and dustless work in close quarters demolished 35,000 cu ft of reinforced concrete in a 910-ft-long, 25-ft-tall railway deck in Kawasaki, near Tokyo.



Impact: Steel frame of breaker unit contains saddle at one end, traveling cutting blade at the other. Shuttling blade, driven by a hydraulic cylinder, demolishes concrete into 20-in. cubical segments.

The vice-like breaker units tilt and pivot to 33 ft high at the end of a three-section steel boom mounted on a 33-ton crawler crane. One end of the breaker's steel frame contains a saddle; the other end, a 12-in.sq chisel blade on a block hydraulically driven forward to the saddle and back again in shuttling sequences.

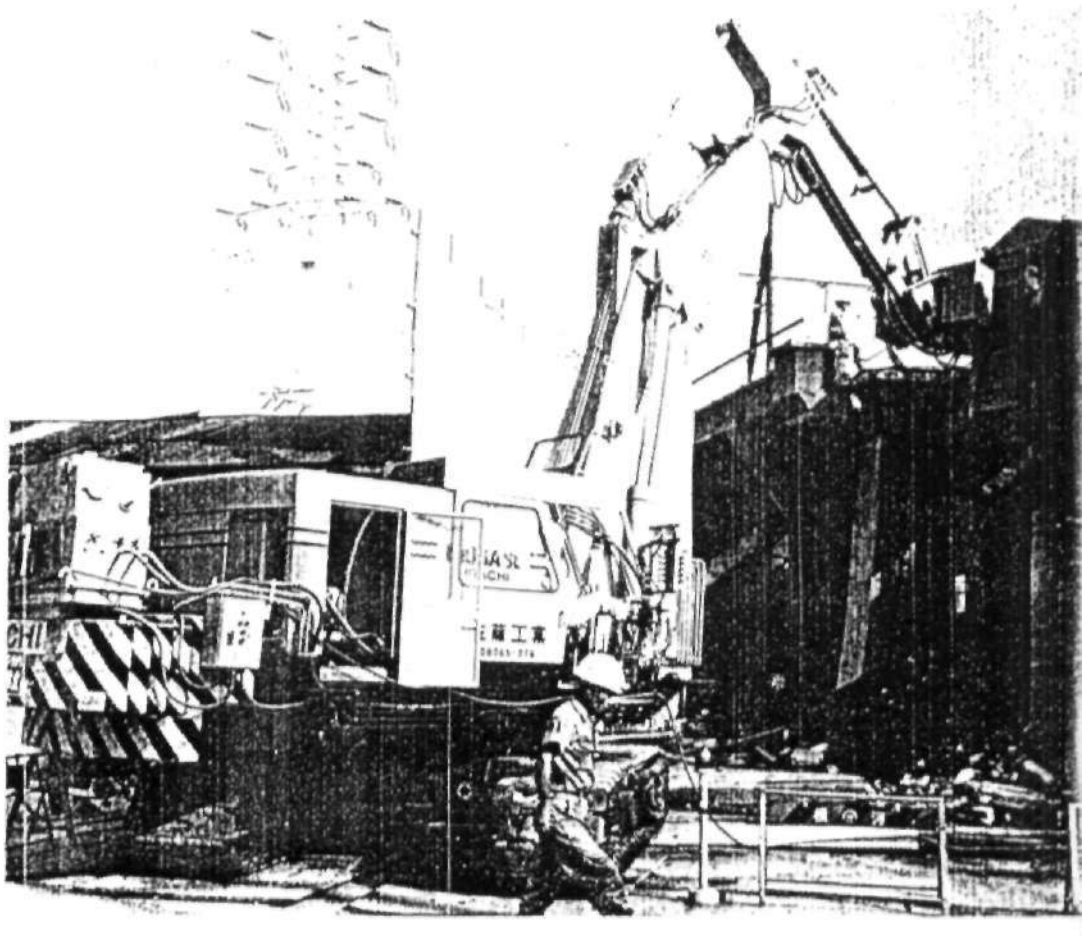
Each machine's blade initially cracks concrete with a 220-ton thrust. Then, with thrust reduced, the blade slices through the wedge, cutting concrete into 20-in.-cubes. Larger rebars must be cut by torch. (The railway deck's concrete included 30-in.-sq columns, 25 × 37-in. girders, 9-in.-thick slabs, and rebars over 1 in. in dia.)

Each machine, operated by one man, demolished an average of 133 cu ft per 9-hr shift. Maximum demolition by one machine was 518 cu ft per day. Working life of a breaker blade is 35,000 cu ft.

The 230-ton, 20-in.-stroke hydraulic cylinder that drives the chisel blade is powered by two oil pumps producing a maximum pressure of 7,610 psi. Pairs of cylinders with 5.6 and 5.7-in. strokes, respectively, turn the breaker unit 135 deg to either side, and tilt it 90 deg up or down. Each of the boom's three sections is controlled by 60-in.-stroke cylinders powered by the crane engine's 2,418 psi oil pump.

Because the gap between the chisel blade and the standard saddle closes from 37 in. maximum to a 18-in. minimum, an auxiliary steel block was placed under the saddle to further reduce the opening for the blade thrusts into the thin floor slabs.

Japan National Railway developed the breaker jointly with Sanwa Kizai Co.



APPENDIX IV Obtained from Shutjen and RamaKrishnan (1974)

Optimum-Mixture-Design Procedure

The sequential steps for optimum mixture design of gap-graded concrete are as follows:

(1) Note the required 28-day compressive strength. Turn to Fig. 1a. Enter at the "compressive strength" value on its scale until hit the curve in Fig. 1(a), drop to abscissa and note the "optimum cement content" value. Then turn up until hit the curve in Fig. 1(b), turn to the left scale and note the "water-cement ratio."

(2) Turn to Fig. 2. Enter the "optimum cement content" value on its scale, turn up and reflect to the left scale, and note the "aggregate-cement ratio."

(3) Move to Fig. 3, enter "water cement ratio" on its scale, turn up and reflect to the left scale, and note the "Vebe time."

(4) Using results of Steps (1), (2), and (3), calculate weights of aggregates and water for each cubic yard of concrete.

(5) Unless otherwise more accurately determined for given coarse and fine aggregates, they may be apportioned by weight as 0.635 coarse and 0.365 fine and use size ranges given in Table 2.

(6) Adjust water requirement with moisture content and absorption capacity of aggregates.

(7) Add appropriate kind and amount of additives as mix and service conditions would require.

(8) Verify mix design by tests and revise if necessary.

Commentary on the Proposed Method and Procedure

The above procedure has been evolved from optimal test results presented in Figs. 1 to 3, and is applicable to the type of coarse and fine aggregates used in this investigation, the mixes containing 5 percent (by volume) entrained air. For these mixes, the above procedure directly gives the quantity of cement per cubic yard of concrete, water-cement ratio, aggregate-cement ratio, the workability in terms of Vebe time, and the amount of vibration time required for proper consolidation.

When the specific gravities of the aggregates available are considerably different from the ones used in this investigation, the following slightly modified procedure is recommended: (1) Determine the quantities of cement and water from figures 1(a) and 1(b), then (2) with a knowledge of the desired air-content and specific gravities of the materials to be used, calculate the absolute volume of aggregates that will be required to produce a cubic yard of concrete. The mixture proportions so obtained could be verified by tests and revised if necessary.

For the majority of optimum mixes, Vebe time varies from 4 seconds (for about 4000-psi concrete) to 9 seconds (for about 2500-psi concrete) which correspond to slumps of 2 1/2 in. and 1/8 in. respectively. The present laboratory studies show that all these mixes can be properly consolidated and well finished. With the availability of modern vibrating equipment, there could be no problem at job sites to achieve full compaction.

Although the optimum mixture design procedure has been based on the gradings of aggregates given in Table 2, for any locally available sound aggregates, it is emphasized to conduct pilot tests to determine if there be better gap gradings for coarse and fine aggregates.

Table 1. Optimal Data and Test Results for Gap-Graded Concrete

Maximum Size of Coarse Aggregate (in.) (1)	Cement Content (lb/cu yd) (2)	Water-Cement Ratio (by wt.) (3)	Aggregate-Cement Ratio (by wt.) (4)	Vebe Time (sec) (5)	28-Day Compressive Strength (psi) (6)
1/2	825	0.35	3.40	9	7369
	655	0.45	4.50	7	6169
	455	0.55	7.00	5	4784
	445	0.65	7.00	4	3774
3/4	765	0.35	3.75	9	6819
	530	0.45	6.00	7	5939
	540	0.55	5.50	4	4279
	440	0.65	7.00	2	3499
1	725	0.35	4.20	8	6534
	535	0.45	6.00	8	5061
	415	0.55	7.00	7	4509
	400	0.65	8.00	5	3311
1 1/2	675	0.35	4.50	8	6219
	540	0.45	6.00	6.5	5061
	430	0.55	7.50	4	4141
	365	0.65	9.00	4	3614

Table 2. Gap Gradings of Coarse and Fine Aggregates for Gap-Graded Concrete

Coarse Aggregate (63.5% by weight)*		Fine Aggregate (36.5% by weight)*	
Sieve Size (in.)		Sieve Size (No.)	
Passing	Retained	Passing	Retained
1 1/2	1	4	8
1	3/4	8	16
3/4	1/2	8	16
1/2	3/8	16	30

*These percentages were experimental results for the crushed limestone and sand used in the authors' investigations. For different aggregates, the optimum percentages may be slightly different.

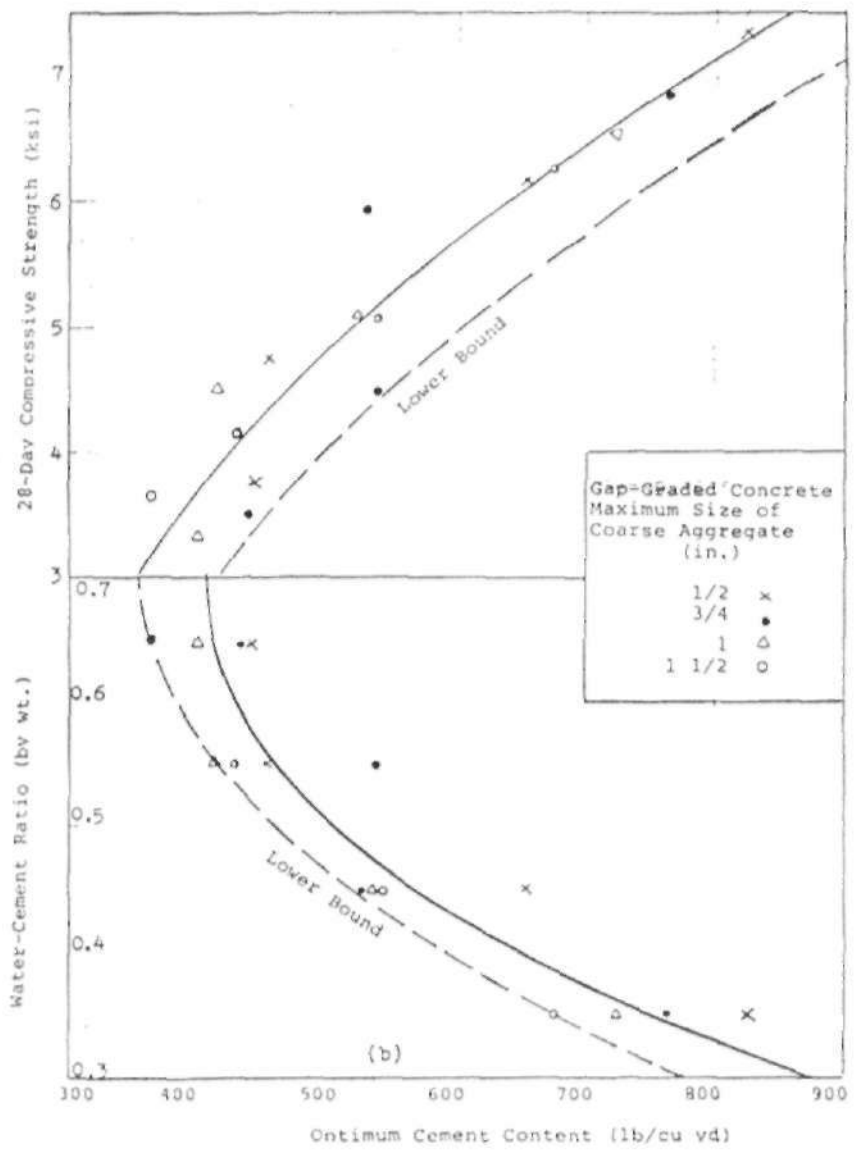


Fig. 1 Relation of "Optimum Cement Content" with (a) 28-Day Compressive Strength and (b) Water-Cement Ratio

optimum mixture proportioning

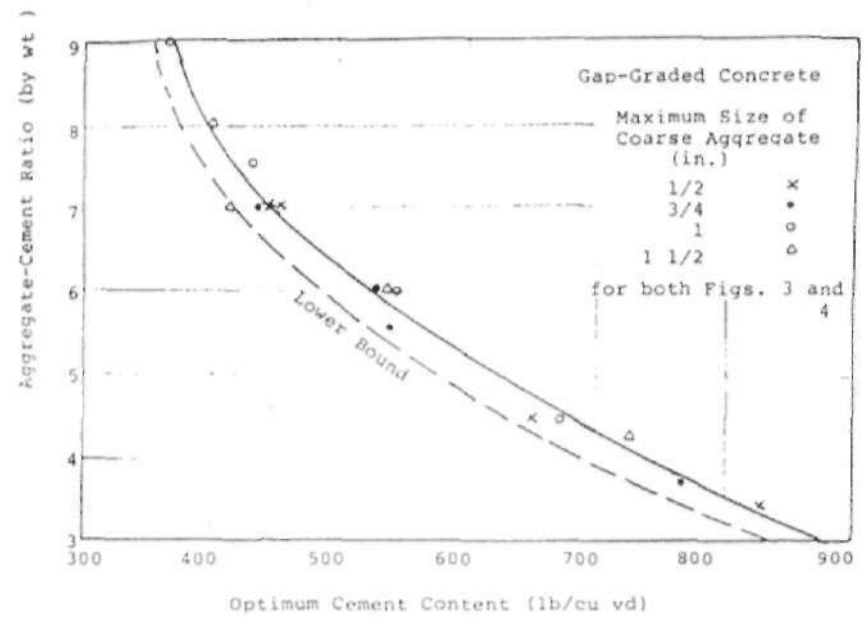


Fig. 2 Relation of "Optimum Cement Content" with Aggregate-Cement Ratio

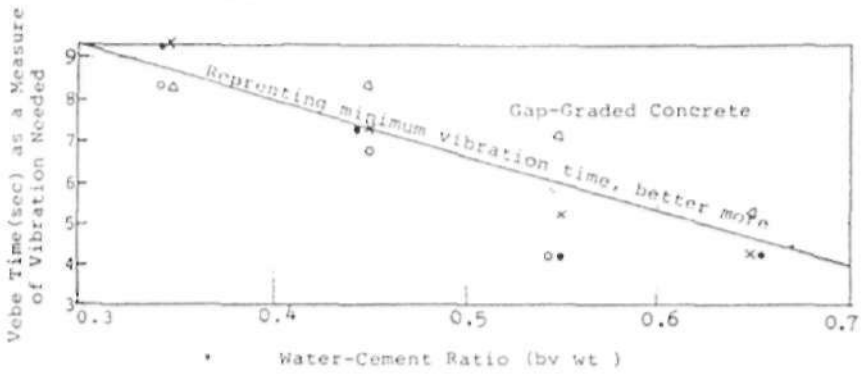


Fig. 3 Relation of Water-Cement Ratio with Vebe Time