PROPOSED DESIGN AND CONSTRUCTION GUIDELINES FOR LABOUR - INTENSIVELY BUILT RUBBLE MASONRY CONCRETE STRUCTURES WITH PARTICULAR REFERENCE TO ARCH BRIDGES

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A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree Doctor of Philosophy.

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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31ST day of MARCH 2000

ABSTRACT

Rubble Masonry Concrete (RMC), a particulate composite of large uncut boulders, manually embedded into a mortar matrix, was used in Roman times for constructing robust physical infrastructure, some of which survives. A renaissance of RMC usage has resulted in recognition of its potential to provide competent infrastructure and create employment for the unskilled without costing a premium. Despite numerous successes, the potential of RMC may be threatened by an absence of knowledge of its mechanical properties and a lack of appreciation of the requirements for humans to labour effectively.

This thesis explores the mechanical properties and behaviour of RMC as well as physiological factors which govern the physical work capacity of the targeted labour-force before proposing guidelines towards the rational design and manual assembly of RMC structures.

In addition to factors known to govern the properties of conventional concrete, potential anisotropy (a consequence of an inherently predominant orientation of elongated inclusions), relative inclusion size and inclusion contiguity appear to characterise RMC. It is hypothesized that as a result of this contiguity, RMC may exhibit a reduced thermal contraction coefficient below its placement temperature; a contributing factor to its resistance to post-hydration cracking. Ultimate failure and deformation of RMC under uniaxial compressive load appear to be governed by mechanisms which evolve between boulder inclusions, often accompanied by rock fracturing as a result of high inter-particle bearing stresses. Fostering of interfacial bond appears to delay the onset of these mechanisms.

Physiological investigation found the cost of human energy high when quantified in terms of the equivalent energy contained in diesel fuel and bread. However, when human-labour is effectively utilised, its versatility, energy efficiency and freedom from fixed ownership costs, enhance its competitiveness, particularly where rival machinery is sub-optimally utilised. Means to improve human-labour effectiveness are discussed.

Based upon these findings and experience elsewhere, RMC material specifications and design and construction guidelines for RMC arch bridges of determinable reliability are proposed. They include a proposal that a high partial material factor be applied to RMC and indicate ways to exploit RMC's anisotropic properties to advantage in highly stressed applications.

CONTRIBUTION TO KNOWLEDGE

This investigation has traced the evolution of Rubble Masonry Concrete (RMC) since Roman times and characterised the modern so-called 'Zimbabwe method' of placing RMC. Factors which enhance the competitiveness of RMC over conventional alternatives are identified.

This is the only study to have explored and measured physical properties of RMC by means of large-scale physical tests. This necessitated the development of several new testing procedures and instruments including:-

1) A compressive strength test to measure the resistance of 500 mm cubic specimens to uniaxially applied load.

2) Apparatus for measuring the modulus of deformation and lateral dilation ratio of RMC.

3) A sensitive mechanical strain cell amplifier for measuring small live-load induced strains in RMC structures to validate theoretical predictions of finite element models.

An hypothesis is presented which, if correct, provides an explanation for the apparent absence of post-hydration cracks in large monolithic RMC structures where theoretical models, assuming concrete values, predict cracking.

By means of a comprehensive study of medical and physiological literature, the targeted unemployed southern African workforce is characterised, in terms of its health, nutritional status and capacity to perform hard manual labour. The cost of human energy is quantified in terms of diesel fuel and bread. These results confirm the importance of conserving human effort and they provide an objective basis upon which to question minimum wage remuneration.

Based on the findings of this study and experience elsewhere, material specifications and design and construction guidelines for RMC arch bridge structures are formulated and proposed. These are the most comprehensive RMC design aids in existence.

for Christine, my Beloved Wife

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In assembling this thesis, I received invaluable assistance from many people. To thank them all would take several pages. However, it would be remiss of me not to mention the names of a few people without who's help I could not have succeeded.

Firstly, my wife Christine has sacrificed more than just a few holidays and far too many of her own ambitions over the past five years to release more of my time towards this doctorate. She has been a pillar of strength and support and has shown the endearing patience of a saint. God bless you my Angel.

My supervisor, Professor Robert McCutcheon, believed in me, gave me continuous encouragement and tactfully guided the development of my work without unnecessarily constraining my curiosity to explore beyond what I had strictly proposed.

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I am privileged to have been able to turn to a number of other eminent authorities for advice in their fields of expertise. I thank them most sincerely for their trouble in helping me improve upon my initial inadequate efforts:- Professor Geoff Blight from the Department of Civil Engineering at Wits guided me on the planning of my research. My late uncle Professor Neville Cook from Berkley provided me with a lot of motivation from the opposite side of the earth and taught me how to look for parallels when exploring new territory. Dr. Mitchell Gohnert from the Department of Civil Engineering at Wits taught me the basis of finite element analysis and recommended a sensible method of analysing arches. Professor Paul Fatti from the Department of Statistics at Wits advised me how best to draw conclusions from my very small populations of data. Dr. Gary McMichael checked the accuracy of my medical statistics in Chapter 6. Professor John Morris from the Department of Building at Wits commented on my investigation into the use of lime as an admixture for mortars. Edith Peters (Futre) from the Department of Physiology of the Medical School of the University of Natal assisted me with metabolic measurements to calibrate a heart-rate monitor. Professor Maurice Viljoen of the Department of Geology at Wits helped me to identify numerous geological specimens.

Others provided assistance by offering their services and making facilities available:- Louis Grobler, the resident engineer who coordinated the construction of dozens of RMC bridges in the Northern Province, and his wife Alona (a maestro in cuisine), overwhelmed me with their generous hospitality while I was away from home doing fieldwork. Rob du Preez and Rod Butler from the Cement and Concrete Institute made their concrete testing facilities available and tested many mortar cube specimens during my career at Wits. The librarians of the Cement and Concrete Institute kept me supplied with information essential to my literature review. Dr. Chandler of the Department of Mechanical Engineering at Wits University made available their 500 tonne Amsler press. Jacob Kroonstuiwer of the CSIR Mine Hoisting Laboratory in Cottesloe made their 1000 ton press available at a reduced fee. Andy Ackroyd of Pioneer Concrete (now Alpha Readymix) donated loads of transit mixed mortar. Trevor Ingram of Concor Technicrete, Olifantsfontein made his yard available for the casting of RMC specimens. Clair Nicolson of the Division of Physical Education at Wits University made available their Sports Science Laboratory, heart rate monitor and metabolic analyser for the physiological testing. Stephen Pienaar of Prokon made software for the finite element structural analysis available, at no cost, and provided much technical advice and support thereafter. Chrispen Pemberto Pigget of New Dawn Engineering lent me his innovative manually powered concrete mixer to perform physiological tests. Dr. Pine Pienaar of African Consulting Engineers (now Gibb Africa) allowed me to embed strain cell devices in his arch bridge structures and gave me permission to publish some of my findings. Henk Scheepers of H & H Civils, Louis Trichard made up large cubic specimens of RMC during the construction of Maritsane Dam and Transported them to Johannesburg free of charge. Robert Sik of Micros Systems (Pty) LTD lent me a vehicle weighing device to measure live-loads on RMC arch bridge structures and Professor Ronnie Schloss of the Dept. of Building at Wits lent me a computer for a considerable time after my resignation.

Some of my students from the Dept. of Building at Wits took an interest in my research and assisted me with the testing of some unwieldy specimens -Nestor Dzormeku, John Roxburgh, Michael Rosenmann, Benjamin Fine, Gareth Letcher and Michael Pearmain. The latter five (all undergraduates) pursued their own research projects investigating various aspects of RMC. I have incorporated some findings of two of these discourses in this thesis.

I persuaded a number of authorities to join me as coauthors in disseminating my progress in accredited refereed journals:- Professor Robert McCutcheon, Professor Geoff Krige, Professor Yunus Ballim, Edith Peters (Futre), Dr. Mitch Gohnert, Louis Grobler, Dr. Dellelegne Teshome and Benjamin Fine. The journal referees who edited these submissions deserve credit for correcting more than a few grammatical errors.

It was a privilege to have been able to discuss my work with several engineering practitioners who have had first hand experience working with rubble masonry concrete:- Altus de Beer, Alan Chemaly, Louis Grobler, Pen Mainwaring and Quentin Shaw.

I was aided by the efforts of Wim van Steenderen and fellow post-graduate students from Professor McCutcheon's Research Centre for Employment Creation in Construction, who arranged numerous discussion seminars where they patiently endured verbal accounts of my progress or the lack of it. These sessions stimulated valuable debate and helped me focus and direct my efforts more profitably.

Special gratitude is owed to John Lane, retired director of the Concrete Manufacturer's Association who has patiently edited and guided my work with uncommon intelligence and sensitivity during the past eight years.

My colleagues at the Cement and Concrete Institute tolerated my absences from duty when I was required to make changes to my initial drafts and willingly shouldered an extra burden of responsibility to make this possible.

Considerable research funding was generously provided by the Kenneth Birch Fund for Bridges and the Department of Transport.

Many others have contributed in various ways for which I am eternally indebted.

Thank you all very much.

PREFACE

In August 1994, I accepted an invitation to visit a remote part of the Northern Province of South Africa, called Bolubedu, to witness the unconventional construction of some "hand-made, stone masonry" arch bridges which had successfully beaten conventional tenders. Not knowing what to expect, I departed equipped with a wealth of misconceptions. On arrival, I was surprised to learn that the bridge-builders, over a hundred men and women from the local community, were completing dozens of small arch bridges, apparently with little intervention from elsewhere. They were proud to announce that the only materials purchased were cement and reinforcing steel and that the balance of the cost of these structures was largely reinvested as wages into their community.

As I observed their proceedings, I began asking questions, many of which nobody appeared capable of answering:-What was this 'stone masonry' material called? How strong was it? How did they ensure its quality? Why did they require such vast quantities of reinforcing steel near the tops of the arches?

A fortnight later, I found myself driving back to Bolubedu to measure bridge strains and collect large specimens of this mysterious material for testing. Within a year, the preliminary findings of this investigation were published in the SAICE Journal. Days after this paper left the press, I received enquiries and criticism about its failure to address questions which apparently bore heavily on the minds of engineers who were asking how the labour-content of their projects could be increased.

My curiosity had ignited a myriad of questions and concerns about this material's physical capabilities and its potential to create employment. Reason dictated that more effective ways of using this 'stone masonry' would avail if its mechanical properties and physical behaviour were better understood. I became increasingly conscious that physiological factors might impact on the effectiveness of these human labourers, especially the very poor. Given my background and fascination with human physiology and energy conservation, I felt the calling to test these convictions. This was possible because I was in the fortunate position of working for the University of the Witwatersrand where I was not only afforded the opportunity to indulge my curiosity, but actually encouraged to do so. I broached the point of no-return.

This Ph.D. thesis is the fruit of that compulsion.

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NOMENCLATURE

In the context of this manuscript, some of the following terms may contain subtle variations in meaning beyond their common usage.

Aelotropic (Anisotropic). Possessing different physical properties in different axes.

Cement. A generic term for binders based on portland cement clinker but not excluding cements containing extenders such as slag and fly ash.

Centering. The temporary framework that supports and gives shape to the intrados of a masonry arch until it can support its own weight.

Crown. The midspan masonry directly above the aperture/s of an arch.

Dessication shrinkage. Shrinkage caused by loss of moisture after the mortar has initially set.

Deuteric (Synantectic). The term applied to alterations in a body of igneous rock produced by the action of vapours and volatiles, which are derived from the magma itself during the latter stages of consolidation.

Energy. The ability to do work.

Extrados. The outer circumference/curve in an arch structure (opp. *Intrados*).

FACT (Fines Aggregate Crushing Test). A standard test method (SABS method 842:1994) whereby the force required to crush a prepared aggregate sample, to the extent that 10 % of the material will, after crushing, pass a sieve of specified aperture size is measured.

Fractal nature. The tendency of small fragments of rock to resemble their larger counterparts in shape and angularity due to inheritance of planes of structural weakness from the parent rock.

Heterogeneity. Not of uniform composition; showing different properties in different portions. In RMC, heterogeneity is a function of the ratio of inclusion size to specimen size.

Intrados. The inner circumference/curve in an arch structure (opp. Extrados).

Joule (J). That amount of energy liberated when a force of 1 Newton acts over a distance of 1m (1J = 1Nm). (This is the SI unit of work.)

Kilocalorie or **Calorie** (spelt with a capital C). That amount of energy required to heat 1 kg of water by 1°C from 14.5 °C to 15.5 °C. 1 Calorie = 4.1855 kJ.

Labour-intensive construction. The "intensive" deployment of human labour for the cost effective and productive execution of a project. It does not imply the exclusion of conventional machinery in cases where human labour is inappropriate or inefficient.

Lateral dilation ratio. Strain in rubble masonry concrete which occurs orthogonal, in all directions, to the principal compressive stress. The lateral dilation ratio is analogous to Poison's ratio but not limited to the material's elastic phase.

Lime. The hydroxide of calcium ($Ca(OH)_2$) and/or magnesium ($Mg(OH)_2$) brought about by the slaking of calcium oxide (CaO) and magnesium oxide (MgO) respectively.

Melange. French word for a mixture of relatively large, competent blocks within a matrix of finer and weaker texture.

Modulus of deformation. The ratio of stress divided by strain in a material which may not exhibit fully recoverable elastic properties.

Portland cement. The generic term used to distinguish the hydraulic binder formed by grinding clinker with a small proportion of gypsum from traditional hydrated lime binder. The term "Common cement" used by SABS ENV 197- 1 is deliberately avoided where it would exclude the many masonry cements which have been used by some RMC designers.

Power. The rate at which work is done.

Repeatability. A lengthy discussion of this term is given in BS 5497. In essence, repeatability is a measure of the variability among replicate test results obtained on the same material within a single laboratory by one operator.

Reproducibility. A lengthy discussion of this term is given in BS 5497. In essence, reproducibility is a measure of the variability among replicate test results obtained on the same test material in different laboratories.

Rubble Masonry Concrete (RMC). A particulate composite of large irregular boulders within a mortar matrix. Other names which have been used to describe this material include Bastard Concrete, Random Rubble, Rubble Masonry, Random Rubble Rock Masonry, Rubble Rock Masonry, Rock Masonry, Uncut Rock Masonry, Uncut Stone Masonry and Muratura a Sacco (Italian name).

Shape factor. The surface area of a boulder inclusion relative to the surface area of a sphere of equal volume.

Specific surface area (Specific surface). The ratio of the total surface area to the total absolute volume of a mass of particles. The smaller the particles, the larger their specific surface area.

Stiffness. A generic term used to describe a material's resistance to deformation. It is not limited to the elastic recoverable component (elastic modulus) but may include non-recoverable deformation as well.

Thermal contraction coefficient. The coefficient of linear thermal expansion of a composite material below its setting temperature.

Third World. An underdeveloped, depressed and chronic poverty area in need of development with little control of its destiny. In contrast, the modern term "developing world" is used to describe aspiring communities who have some control of their destinies.

Unemployed (Jobless). People who want to work and who are available for work but who have not worked for more than a week prior to being interviewed. Towards the end of the period of this research initiative, the definition of 'unemployment' in South Africa changed considerably to exclude people who had not actively sought work in the preceding four weeks. This second definition ignores a significant proportion of working age people who have given up all hope of finding work. Therefore, the first definition is adopted throughout this manuscript as it more accurately reflects the true extent of joblessness in the South African economy.

Watt (W). A joule per second ($1W = 1J.s^{-1}$). (This is the SI unit of power.)

1st Law of Thermodynamics. In a system of constant mass, energy can be neither created nor destroyed.

ACRONYMS

BMR.	Basal Metabolic Rate
FACT.	Fines Aggregate Crushing Test
GGBS.	Ground Granulated Blast Furnace Slag
ILO.	International Labour Organisation
ITZ.	Interfacial Transition Zone
NPWP.	National Public Works Programme
RMC.	Rubble Masonry Concrete

A FRIENDLY NOTE TO EXAMINERS

If you find a mistake in this thesis, please consider that it may have been put there for a purpose. I have endeavoured to include something for everyone. Some readers are always looking for mistakes.

(Acknowledgement NSRI Sea Rescue)

CHAPTER 1

INTRODUCTION

1.1 THE PROBLEMS OF UNEMPLOYMENT AND POVERTY AND THE ROLE OF LABOUR-INTENSIVE TECHNOLOGIES IN REDUCING THEM

One of the foremost problems facing governments of developing countries, particularly in southern Africa, is the extremely high level of unemployment and its accompanying poverty. At the same time there is often a backlog of much needed physical infrastructure including water supply and transportation networks. These problems are set within a low-level of individual and community capacity in both technical and institutional terms(1.1,1.2).

However, if some of this required physical infrastructure were constructed and maintained by using labour-intensive methods, then presumably these problems could both be addressed simultaneously, and institutional capacity and local skills development could be enhanced.

Over the past two decades, this concept of deploying labour-intensive methods for the inevitable construction and maintenance of physical infrastructure, throughout the developing world, has progressed from being a hypothetical possibility to a practical reality(1.3). Numerous manual techniques, particularly in road construction, have been tried, tested and refined(1.3). Following many successful precedents elsewhere in Africa, several authorities (including McCutcheon(1.2), the International Labour Organisation (ILO)(1.4) and others(1.5-1.8)) have proposed the adoption of similar properly executed employment-creation programmes, based on the use of labour-intensive methods, as one means of addressing unemployment in southern Africa.

Recently, Rubble Masonry Concrete (RMC), {a building material comprised of large irregular stones manually embedded into a mortar matrix[1*]} has demonstrated much potential for

[1*] A more comprehensive definition of RMC is presented in Chapter 2.

contributing to the satisfaction of these needs in southern Africa. Several RMC structures have been designed and built in competition with conventional alternative designs(1.10-1.19). None of these RMC projects benefited from any standard codes of practice or even modest design and construction guidelines. They were designed and built without quantification of the range of the material's mechanical properties or knowledge and understanding of its limitations, and behaviour. This thesis will endeavour to redress this situation.

1.2 THE NEED FOR IMPROVED TECHNICAL KNOWLEDGE OF THE PROPERTIES, BEHAVIOUR AND USE OF RMC

Lack of knowledge of the mechanical properties and physical behaviour of RMC, despite it being one of the oldest construction materials, is probably a result of the difficulty in testing a composite containing enormous boulder inclusions. In a comprehensive review of literature pertaining to RMC, which included several documents from the last century, only one reference(1.20) to the physical testing of large specimens of RMC could be found. It cites no details about the nature of these tests.

Consequently, present day engineers have been forced to rationalise their designs with reference to nothing more than the limited precedent set by a handful of Zimbabweans who have in the recent past designed and built their structures empirically. Designs have therefore tended to be conservative and restricted to small projects to minimise the risks which could arise from the prevailing extent of ignorance. Nevertheless, there are numerous(1.10-1.19) cost effectively executed projects which have evoked widespread public interest and support in the wake of their successes. It would appear that this material has won the approval of many communities, policy makers and environmentalists and that this construction method should be pursued.

While a history of more than two decades of experience of RMC in Zimbabwe provides, and will continue to provide a very useful reference, there is justifiable concern that to continue to base future designs upon this limited precedent alone may prove to be a dangerous practice. Firstly, Zimbabwean engineers currently appear to "rationalise" their margin of material safety by limiting compressive stresses in RMC to a fraction of the 28 day strength of their mortar (as evidenced by 100 mm cube strengths)(1.21), yet they do not appear to have established any relationship between the mortar cube strengths and the RMC composite strength. Secondly, Zimbabwean experience has been almost exclusively limited to the use of granitic inclusions on granitic foundations(1.21,1.22). Thirdly, the Zimbabweans apparently assume RMC to share the characteristics of conventional concrete, yet there is convincing evidence that certain characteristics of RMC may be unique. For example, the large aggregate inclusions in RMC butt tightly and intimately against one another and most large monolithic RMC structures do not appear to suffer post-hydration thermal and drying-shrinkage cracks - in fact, there is an apparent absence of such cracks altogether, even in their widest large valley arch dams(1.21,1.22). This suggests that the Zimbabwean composite may have a lower elastic modulus and/or a lower coefficient of thermal expansion than conventional concrete, and/or that limited thermal strains result from their relatively temperate climate, and/or that the mutual exclusivity of maximum load and minimum temperature induced tensile stresses might mitigate the otherwise critical case. While this study can not hope to provide answers to all of these issues, it is a point to remember that, despite being a significant reference, Zimbabwean experience will not necessarily apply elsewhere. Engineers in countries like South Africa are likely to encounter a broader spectrum of geological possibilities and climates.

In consequence to these concerns, several authorities(1.11,1.21-1.24) have cautioned that unless the mechanical properties and physical limitations of RMC are better understood and quantified, engineers will not be in a position to confidently design more ambitious and economical structures of determinable reliability in the future.

In addition to the use of this knowledge to improve the design of new structures, such knowledge may be valuable in auditing the soundness of existing structures. For example, Burland(1.25), who developed a theoretical model capable of simulating the history of the inclination of the Leaning Tower of Pisa, to quantify its low margin of safety against overturning, has cautioned of another imminent failure mechanism whose threat is presently indeterminable. It is the type of instantaneous structural masonry collapse which brought down the Italian Civic Tower of Pavia, killing people in 1989. Pisa is supported by an annular core of "muratura a sacco" (mortar and rubble). Immediately above the level of the first cornice, is a highly stressed section owing to the presence of a staircase passing through this masonry at the critical overhanging south side. Burland (1.26) admits his defeat in estimating a margin of safety here, only for want of knowledge of the properties and behaviour of this core material.

At the outset, three fundamental questions regarding the mechanical properties of RMC prevail:-

1) How do the mechanical properties of RMC differ from those of conventional concrete and to what extent, if any, can the behaviour of conventional concrete be assumed to apply to RMC?

2) How variable are the mechanical properties of RMC and what range of values should the designer anticipate in practice?

3) What are the phenomena which govern these mechanical properties and to what extent can they be manipulated to engineering advantage?

Preliminary consideration of these questions led to a pilot study[1.27] (see Appendix 1) which involved instrumenting a small RMC arch bridge with strain measuring devices and collecting cubic specimens of RMC for compression testing. The findings of this pilot study led to the refinement of research objectives and a better appreciation of the challenges in exploring this material.

1.3 SCOPE AND OBJECTIVES

Prerequisite to the commencement of a thorough investigation of RMC is the establishment of its potential as a sustainable, labour-intensive and employment-creating technology, capable of making use of local materials to provide cost-effective infrastructure. In the event of a positive outcome, the primary objective is to explore the mechanical properties and physical behaviour of RMC so as to expand the base of knowledge required for rational structural design. Based upon this acquired knowledge as well as past experience, the ultimate objective is to propose recommendations for the rational design and construction of RMC structures of known reliability, with particular reference to arch bridge structures, given conditions and resources typically encountered in a region such as southern Africa. Since RMC is a labour-intensive technology, the physiological requirements for humans to labour effectively warrant consideration in this process. These proposed recommendations are not intended to be used as a code of practice or to replace the engineer's conscience nor are they intended to serve as a layman's instruction manual. Instead, they are intended as guidelines to aid responsible engineers in the design and specification of better RMC structures in future. Hopefully, these guidelines will be tested, challenged and substantiated by practitioners to evolve a comprehensive code of practice in the near future.

1.4 STRUCTURE OF THE REMAINDER OF THIS THESIS

Chapter two reviews the existing literature pertaining to the history, properties and use of RMC. It provides the context in which RMC may best provide infrastructure for developing communities. This chapter satisfies the prerequisite described above (to investigate the potential of RMC as a labour-intensive, employment creating technology) and provides a point of departure for the acquisition of knowledge in the following chapters.

Based on the experience of the pilot study[1.27] (see Appendix 1), a cubic specimen test method was proposed[1.28] to gain an indication of the range of strength and behaviour of RMC under uniaxially applied compressive load (see Appendix 2). This method was adopted and adapted for other tests. The results of numerous series of these tests, undertaken to characterise the material's behaviour, variability and compressive strength under uniaxially applied load, are presented in Chapter three.

Chapter four explores the material's deformation behaviour via interpretation of results of experiments conducted on physical specimens and predictions derived from theoretical models (see also Appendix 3).

Chapter five presents an hypothesis (yet to be quantitatively validated) which provides an explanation for the apparent lack of visible post-hydration cracks in large monolithic RMC structures.

Before drawing conclusions and proposing guidelines for the design and construction of RMC structures, the physiological requirements and limitations of the targeted human population who will build these structures deserve some consideration. Physiological factors are inflexible and a lack of their appreciation may jeopardise the success of an otherwise perfectly planned project. Therefore, Chapter six reviews the physical status and capacity of the targeted populations to undertake heavy manual labour. Based on a study[1.29] of a subject, termed *human labour thermodynamics* by the author (see also Appendix 4), the cost and scarcity of human energy is quantified with reference to the costs of diesel fuel and bread. Tasks which may be very taxing of human energy and/or more efficiently undertaken mechanically are identified. In addition, several fundamental physiological considerations which could affect human productivity in building RMC structures are briefly discussed.

Based on the findings of chapters three to six, Chapter seven proposes some material specifications guidelines to aid designers intent on making maximum use of labour and materials sourced within the immediate vicinity of their projects but without compromising the quality and viability of their structures. This chapter includes considerations for selecting suitable rock, ingredients for ideal mortars and a proposal[1.30] to use hydrated lime as an admixture (see also Appendix 5).

Chapter eight is devoted to the proposal of design and construction guidelines for RMC arch bridges. Various theoretical models for predicting working stresses and strains in arch structures, such as finite element models, are discussed and used to explore various design parameters in arch bridges. These theoretical finite element models predicted very low stresses and strains in typical structures. The strain measuring devices cast into the bridge structure during the pilot study confirmed these predicted low order of magnitude stresses but indicated the need for greater instrument sensitivity for more accurate calibrations on such lightly stressed structures. Enquiries established that greater sensitivities were not achievable with commercially available and affordable strain gauges and electronic amplifiers. Consequently, an integrated mechanical strain cell amplifier was developed and tested[1.31] for this purpose (see Appendix 6).

Chapter nine, the conclusion to the research, summarises the main findings and their implications for the design and construction of new RMC structures. Further potential research opportunities are identified and the author's opinion regarding the role of RMC in serving mankind in the future is expressed.

Appendices 1 to 8, contain selected published and unpublished work which complements the main argument but which would detract from the readability of the thesis if it were included in the main text.

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CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 THE PAST ROLE OF RUBBLE MASONRY CONCRETE IN SERVING DEVELOPING COMMUNITIES

RMC (also termed *Random Rubble* by the British[2.1] and *Bastard Concrete* by the Americans[2.2]) has earned itself a reputation as an enduring building material, ideally suited to arches and mass retaining structures which experience little tension and where bulk mass assures stability and rigidity. Before Aspdin's patent to manufacture portland cement in 1824, RMC structures relied entirely upon lime and/or clay as the binder material for the mortar matrix. Nevertheless, many of these ancient RMC structures have stood the test of time and are still in service today, having survived many centuries and a few have lasted over 2000 years[2.3]. Some well known old structures, which rely upon RMC for strength, include Hadrian's Wall[2.4] (122 AD see Figure 2.1), the Tower of Pisa[2.5] (1174), St Andrew's Castle[2.6] in Scotland (1189) and the Good Hope Castle[2.7] in Cape Town (1665).

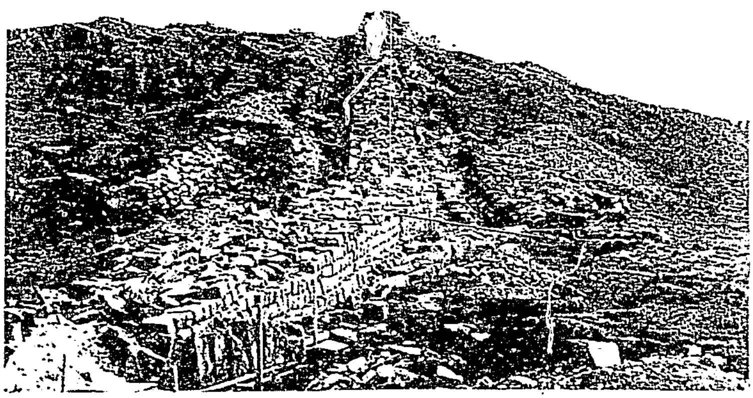

Fig 2.1 A section of Hadrian's Wall near Northumberland[2.4].

2.2 THE COMPETITIVE ADVANTAGE OF RMC BEFORE THE 20^{th} CENTURY

RMC lent itself to the provision of basic infrastructure for previous civilisations because of its efficient use of available resources. The incorporation of large boulders, which exist in abundance over much of the earth's surface, formed the bulk of the composite and made it economical, both in terms of cost, and energy requirements. Mortar, which consumed very costly[1*] binder, was used sparingly by manipulating the boulders to minimise the joint space between them and by carefully packing progressively smaller stones or "spalls" into the remaining voids. Since there were practical limitations to the minimum size of spalls which could be manually inserted between boulders, further mortar reductions were achieved by increasing the size of the largest boulders. About one century ago, the Americans[(2.8)] frequently used very large boulders, aptly named "derrick stones", because they were too large to lift manually and had to be lifted by derricks. These stones were as large as 50 cubic feet (1,4 m^3) weighing up to four tonnes (see Figure 2.2). The British are reported to have used even larger stones weighing up to ten tonnes[(2.9)]. This practice was reported to result in a 50% mortar saving, requiring a mortar volume fraction of only 24%[(2.8)]. Thus, the stone content typically occupied as much as 76% of the composite's solid volume fraction[(2.8)]. By contrast, 19 mm crushed stone occupies about 41% of the solid volume of hand compacted conventional concrete[(2 . Furthermore, the boulder inclusions in RMC required no costly mechanical processing by crushing, screening or blending. Once built, a RMC structure was potentially maintenance free since it could not rot or corrode; instead it would continue to harden and strengthen for years. Thus, it is not surprising that RMC remained extremely competitive during the nineteenth century where it was internationally exploited for building some of the largest dams of that era (see Figure 2.3), many of which remain standing today.

It was only during the later half of the nineteenth century that engineers such as Rankine[(2.17)](1865), Krantz[(2.15)], De Sazilly, Delocre and Levy[(2.9)] began to question the material properties of RMC and apply rational design philosophies to its structural use. Unfortunately,

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The relative cost of binder, prior to 1900, was significantly greater than today. Various attempts to relate the cost of portland cement to the cost of well known commodities such as modern currency[(2.7,2.11)], whisky[(2.11)], houses and motor cars[(2.13)] indicate that its cost, in real economic terms, has consistently decreased several-fold during the twentieth century. Moreover, it has been shown that the amount of cement required to produce a given concrete strength has markedly reduced over this period[(2.14)]. Wegmann[(2.15)] cites the carefully kept records of contractors who built New Croton Dam for New York City between the years 1898 and 1899. The cost of a 100 pound (45 kg) bag of cement was 60 cents when the minimum wage was ten cents per hour and the all inclusive cost of RMC laid in the dam was only US$ 3.028 per cubic yard (US$ 4.28/m^3). To have made equivalent conventional concrete, the cement alone (based on the cement content required to produce 15 MPa concrete today[(2.16)]) would have exceeded 80% of this cost.

their efforts had little time to evolve since a number of factors began to make RMC redundant, of which, perhaps the most significant occurred during the building of Panama Canal in the first decade of this century. The locks, dams and other concrete structures were to contain a volume of 3.7 million m^3 of concrete; a quantity unprecedented by any other project in history[2.18]. The accompanying developments in machinery greatly reduced the cost of crushed aggregate and cement and significantly improved the quality of the latter[2.19,2.20]. Coupled with an increasing cost of labour and a desire to reduce construction time, these factors brought about the evolution of a new material called "*cyclopean masonry*" to replace RMC for dams[2.8,2.19,2.20]. Cyclopean masonry differed from RMC, in that concrete was used in place of mortar, necessitating correspondingly thicker joints and consequently the importance of an accurate fit between boulders became less critical[2.8].

Fig 2.2 Croton Falls Dam in construction (1906-1911). It was built across the West Branch of the Croton River to form a storage reservoir to supply New York City[15]. The human figures provide a useful scale to gauge the size of the boulder inclusions.

During the next decade concrete became even cheaper and the tradition of carefully placing large cyclopean inclusions gave way to a new practice of dumping "plums" into con e to enhance its economy - a material dubbed "Concrete Masonry" by the Americans[2.8]. Shortly thereafter, unadulterated concrete, as we know it today, became the norm. Not only could concrete structures be built in less time and at lower construction cost using crushed aggregates and batching plants, but small concrete specimens (typically cylindrical or cubic prisms) could be routinely tested to confirm the concrete's strength and variability. Upon this quantified knowledge, the basis of rational design of more efficient and economical concrete structures of known reliability was founded. Uncertainty as to the possible deleterious effects of dumping large plums into concrete resulted in their prohibition in applications of structural significance by many design codes[2.8,2.20]. Consequently, the pursuit of knowledge about the mechanical properties, behaviour and engineering use of RMC drew to a halt[2.19,2.20].

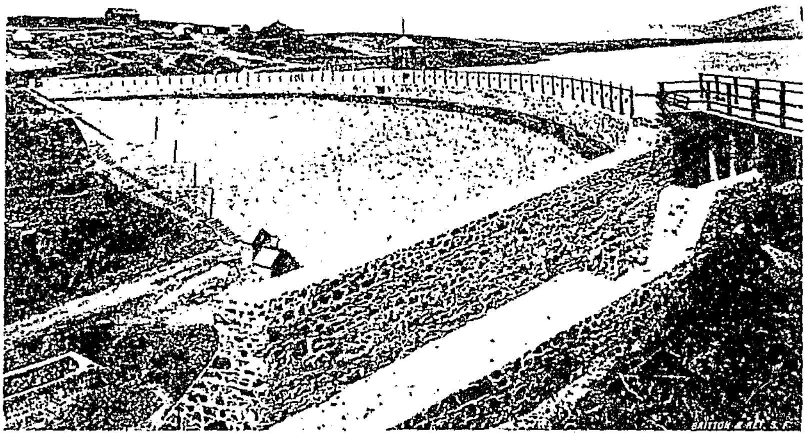

Fig 2.3 Sweetwater Dam in San Diego built in the 1880's[2.2]

2.3 THE RENAISSANCE OF RMC IN THE DEVELOPING WORLD

It would appear that only a few developing countries in Asia[2.21] and Africa continued to use RMC during the twentieth century. In Zimbabwe, a resurgence in the use of RMC followed the unilateral declaration of independence by the Rhodesian Government in 1965, to reduce dependence on foreign currency, particularly for the consumption of liquid fuels and the replacement of machinery[2.22]. Engineers Mainwaring[2.22,2.23], Petzer[2.22], Hasluck[2.23], Wild[2.24,2.25], Robertson[2.25], Wooton[2.26], Stephens[2.26], dos Santos[2.27] and Shelton[2.28] have made many valuable practical contributions by way of empirical design, detailing and construction of RMC arch bridges and substantial dams; although by their own admission[2.25] "on an ad hoc basis and without any code of practice". They were motivated by a need to provide maximum infrastructure with very humble resources rather than by a philanthropic desire to 'hand out' employment. As a result, their design and construction method, now known as the "Zimbabwe Method", has become extremely cost effective and competitive.

2.4 DEFINITION AND CHARACTERISATION OF THE CURRENTLY ADOPTED COMPOSITE LAID BY THE SO-CALLED "ZIMBABWE METHOD" OF PLACEMENT

The Zimbabwean material differs from that used during the previous century in that the maximum boulder inclusion size has been limited to the mass a single man could handle, typically ranging between about two kilograms and as heavy as a man can comfortably lift (about 40 kg). Accordingly, the volume proportion of mortar is significantly greater, typically about 45-55%. First, a thick layer of mortar (typically 150 mm) is spread horizontally (see Figure 2.4) into which the biggest stones are crudely packed as closely as practically possible without resorting to cutting or dressing them. Small stones or spalls are then pushed in between these boulders to reduce the interstitial volume of mortar. Once it becomes difficult to find new spaces for the spalls, a subsequent thick layer of mortar is spread on top of the previous masonry and the procedure of packing more boulders is repeated in horizontal lifts. Unless a deliberate attempt is made to the contrary, boulders tend to be placed with their longest axes and/or planar surfaces horizontal since this orientation is naturally most stable under gravity.

Unlike concrete, where the coarse aggregate particles become coated with a thin layer of mortar which tends to separate each particle from its adjacent neighbours, the boulder inclusions in RMC are usually forced into the mortar until they butt contiguously tight against one another.

Fig 2.4 Crude manual placement of stones into the mortar matrix.

The currently favoured method of construction utilises the most experienced masons to build vertical outer leaves of masonry (typically 200-300 mm wide) with stiff mortar (typically 25 mm slump) to contain the inner core (see Figure 2.5). Less experienced labourers then fill the inner core with higher slump mortar (typically 75 mm) and stone. Methods of compaction, to expel air, range from tamping the mortar with a crowbar, stick or trowel to kicking the rocks with their boots. Nevertheless, large air voids frequently remain beneath large boulders, against horizontal formwork and between tightly fitting rock surfaces.

Because of the low cementitious content of the final product (typically less than 300 kg/m^3) and the relatively slow rate of construction, heat of hydration effects, such as thermal cracking, are effectively eliminated [2.37].

Fig 2.5 Typical division of tasks during the building of Bakubung Dam in the Pilansberg Nature Reserve. The "skilled" labourer on the right is building outer leaves which will act as permanent formwork to contain the more fluid (inner) masonry which is being placed by the unskilled labourer in the centre.

2.5 THE RECENT ADOPTION OF RMC ELSEWHERE IN SOUTHERN AFRICA

During the late 1980's, several southern African authorities including the Department of Transport, the Transkei Appropriate Technology Unit, the National Public Works Department and the Department of Water Affairs and Forestry began to consider labour-intensive construction technologies as a means of combatting rising unemployment levels amongst the unskilled destitute. In search of an appropriate technology to employ the unskilled destitute and provide rural dams and bridges, RMC was used to construct, at least three gravity dams in the

Eastern Cape between 1989 and 1991[2.29] (Figure 2.6), followed by 20 arch bridges in the Northern Province[2.30] between 1992 and 1993 (Figure 2.7). In 1994, two[2.31,2.32] policy documents encouraging the promotion of employment-intensive construction techniques, particularly in the awarding of government tenders, were released. Subsequently, RMC was used to build many more structures, including the Sunday's River Bridge in KwaZulu Natal in 1994[2.33], and several significant dams including Maritsane Dam in Mpumalanga[2.34] (Figure 2.8), the Likalaneng Weir in Lesotho[2.35] (Figure 2.9), Bakubung Dam in the Pilansberg National Park[2.36] (Figure 2.10) and Welgevonden Dam at Moketsi in the Northern Province[2.37].

Most of these projects employed significantly more labourers than conventional designs. For example, Shaw[2.36] states that Bakubung Dam created 9000 person-days of employment, whereas he estimates that a conventional fill dam would have created less than 1000 person-days of employment.

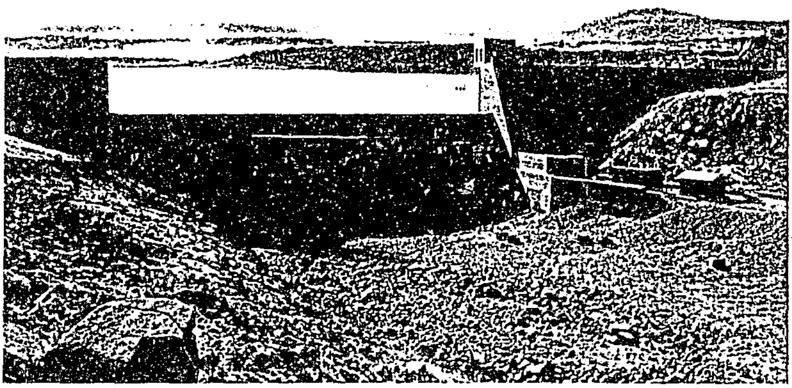

Fig 2.6 The RMC Macubeni Dam built in the Ladyfrere District, Transkei in 1989 with dolerite rock. (Photo courtesy of Campbell De Korte & Thorburn Consulting Engineers.)

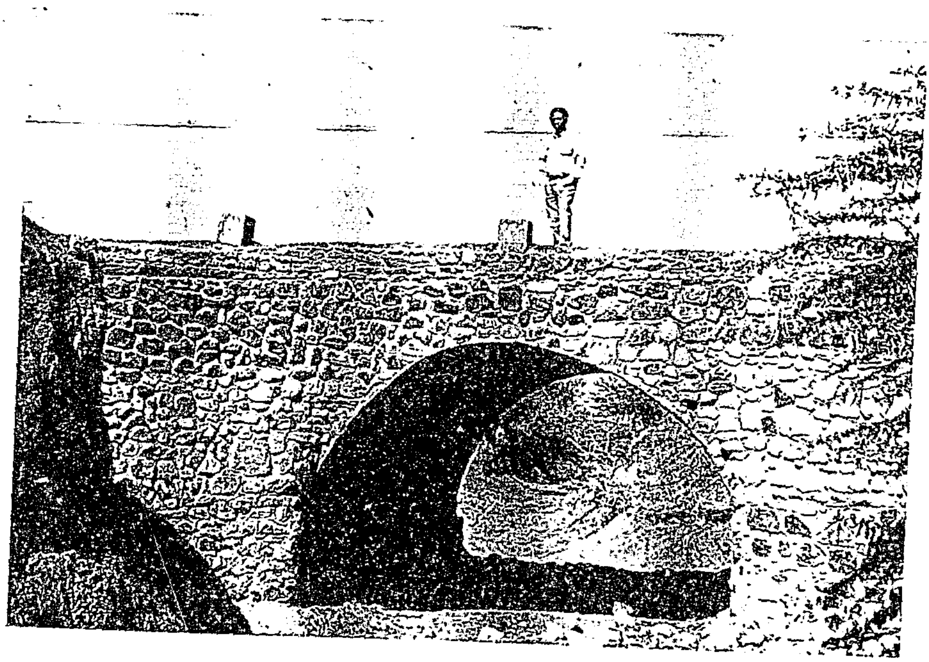

Fig 2.7 One of at least twenty RMC arch bridges built in the Northern Province of South Africa.

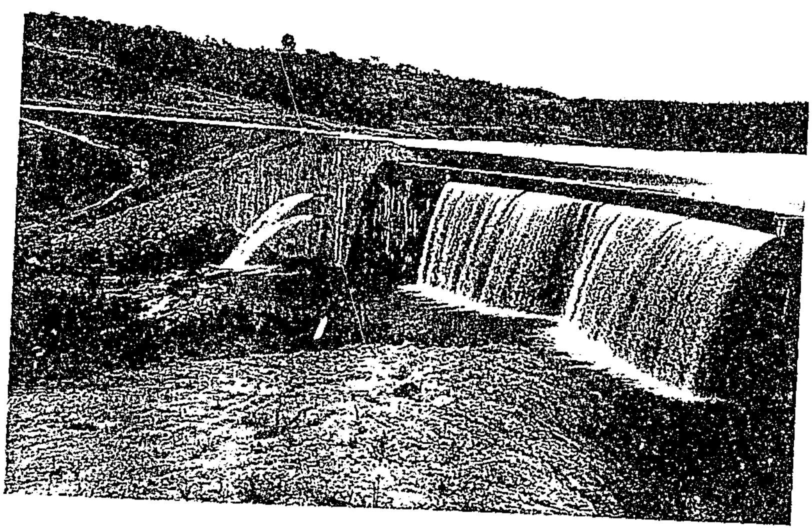

Fig 2.8 Maritsane Dam in Mpumalanga, the largest RMC structure built in recent South African history.

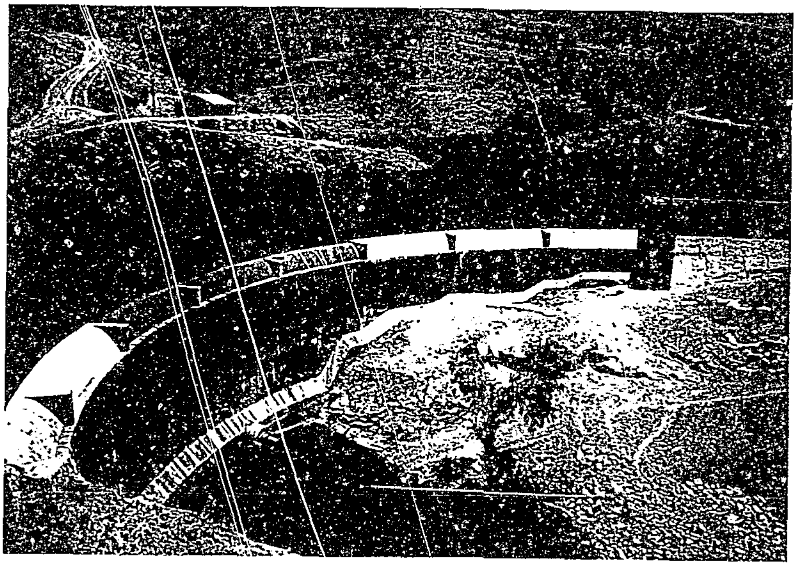

Fig 2.9 The Likalaleng Weir built in Lesotho where difficult terrain made materials' transportation cost significant, thereby enhancing the viability of this RMC structure

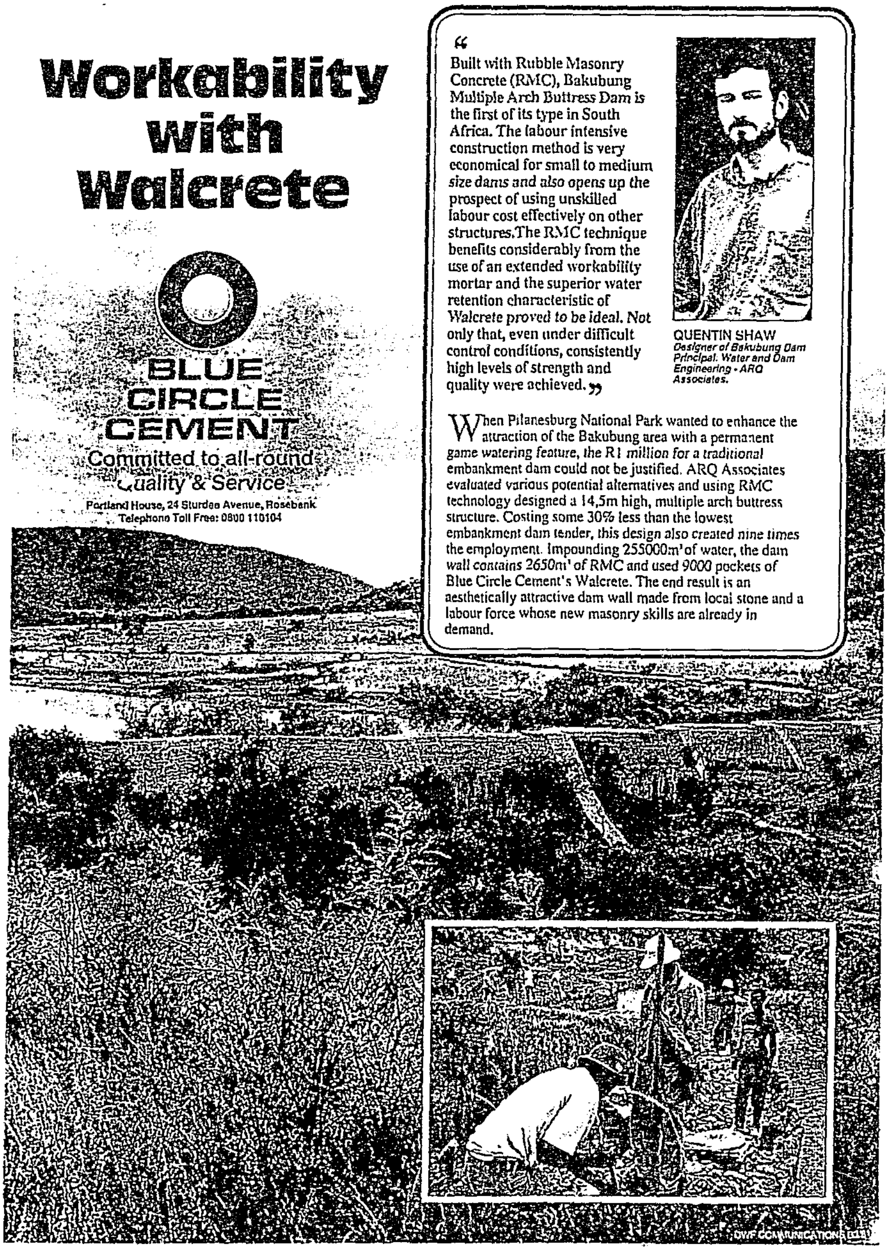

Fig 2.10 Bakubung Dam in the Pilansberg National Park, South Africa, (proudly displayed in an advertisement with its designer).

2.6 THE COMPETITIVE ADVANTAGE OF RMC IN TODAY'S DEVELOPING WORLD

To date, many civil engineering projects which were executed manually, in an effort to relieve unemployment, have incurred a cost premium[2.38-2.41] (when compared to conventional mechanised alternatives), and the "labour-intensive" concept has attracted criticism and condemnation[2.40,2.41]. Indeed, it has been claimed[2.42] that the current view among South African engineers is that equipment is more efficient than labour.

Although increased employment may be shown to have non-quantifiable or qualitative economic and social benefits, there is much evidence to support the hypothesis that projects which incur a cost premium to execute manually, are damaging to a developing country's economy and therefore ultimately unsustainable[2.38,2.39,2.43]. Economists[2.38,2.43] forecast that simply employing more labour, as an input factor of production without a corresponding increase in output, will ultimately have a negative effect on the construction industry, leading to a decline in economic growth and investment. Furthermore, by example of their failures, such projects may even encourage capital intensification thereby defeating their primary objective - to create jobs. To be sustainable, labour-intensive technologies must be capable of competing with conventional mechanised technologies.

The recent advent of RMC structures in southern Africa has demonstrated that economic viability and cost effectiveness of labour-intensive technologies need not be elusive. All the abovementioned RMC structures (Figures 2.6 to 2.10) have been built at considerably lower cost than conventional alternative designs[2.30,2.34-2.37], despite the high remuneration paid to their labour-forces in many cases and a complete absence of any code of practice or even modest design and construction guidelines. For example, Shaw[2.37] states that Bakubung Dam (see Figure 2.10) cost "some 30% less than the lowest embankment tender". Hence, in response to the first objective of this investigation, there can be no doubt that RMC has proven its potential to provide cost-effective infrastructure and employment opportunities. This affirmation has been corroborated in a parallel study by Grobler[2.46] whose *"analyses showed that an investment in this type of infrastructure not only has among the highest returns on investment of all public investment options but, yields by far the highest employment creation per unit invested."*

In an analysis[2.47] of recent experiences, the competitive advantage of RMC, over more conventional mechanised alternatives, was attributed to the following factors:-

1) The only material purchased is cement.

2) Provided the boulders and sand are sourced within close proximity of the site, their acquisition costs may be limited to the wage remuneration of gatherers and possibly blasting costs if rock has to be quarried.

3) Transportation costs are minimised because cement (which typically accounts for only 7% of the weight of a RMC structure) is the only material hauled any considerable distance.

4) Unlike conventional concrete, RMC requires no vertical support during placement, therefore dispensing with the need for much costly formwork.

5) The conservative design approach adopted for most RMC structures results in components with low aspect ratios. This is a considerable advantage since the working face is often large enough to serve as a platform, thereby obviating the need for additional scaffolding.

6) No crushed aggregate is used. Therefore, there are no costs of mechanical crushing, washing and screening.

7) Because the rock is sourced locally, completed RMC structures may be built to blend into their surrounding landscapes by leaving the rock inclusions exposed without any additional costly facade materials. Hence, they are increasingly favoured for the provision of environmentally sensitive infrastructure where costs need to be contained.

Thus, the competitive advantage of RMC appears to emanate not from exploitation of human labourers, but rather the efficient deployment of abundant resources.

2.7 REVIEW OF KNOWLEDGE AND PERCEPTIONS ABOUT THE MECHANICAL PROPERTIES AND LIMITATIONS OF RMC PRIOR TO THIS STUDY

2.7.1 Strength and orientation of boulder inclusions

An appreciation of the significance of rock orientation in masonry appears to have been well established in early history. Most remaining masonry monuments (for example, the remnants of St Andrew's Castle in Scotland) show evidence of a serious effort made to cut and shape the stones so that the joint planes were thin and perpendicular to the principle stresses (at least at the edges if not the core). Whether this was because previous civilisations understood how flat stone faces and thin bedding joints are able to offer bilateral constraint to weak mortar, or whether they simply learned that structures built this way were more reliable, remains unclear. The oldest reference to RMC strength, and the significance of rock orientation with respect to strength, appears to date back to 1865 where Rankine[2.17] evaluated the merits of different forms of masonry in his *Manual of Civil Engineering*. The following two extracts appear under a section entitled "General principles":-

1) *"The resistance of common rubble (RMC) to crushing is not much greater than that of the mortar which it contains; it is therefore not to be used where strength is required, unless built with strong hydraulic mortar."*

2) *"...To build the masonry, as far as possible, in a series of courses, perpendicular, or as nearly perpendicular as possible, to the direction of the pressure which they have to bear; and to avoid all continuous joints parallel to that pressure by 'breaking joint'...To lay all stones which consist of layers or 'beds' in such a way that the principal pressure which they have to bear shall act in a direction perpendicular, or as near to perpendicular as possible, to the direction of the layers. This is called 'laying the stone on its natural bed', and is of primary importance to strength and durability, as has been already explained in various articles."*

Unfortunately, Rankine gives no clue as to the source of these articles but Lenczner[4.44] has shown that the frictional restraint to mortar between bricks affords enough confinement (preventing the mortar dilating) to render the brickwork strength proportional to the fourth root of the mortar strength. Thus, thin parallel joints, perpendicular to the principal stress, effectively eliminate the need for strong binder. Taken to extreme, it is conceivable that a thin layer of loose sand would prove sufficient to separate two bricks under a sustained axial load.

Legislation to govern the maximum allowable working stresses in RMC appears to date back at least to the years 1924 to 1927. American building codes limited the allowable compressive working stresses on RMC, cast in portland cement mortar, in the design of all structures to be built in its cities. On one extreme, Buffalo and Baltimore shared the most stringent limitation of 125 lb. per sq. in. (0.9 MPa) while at the opposite extreme, Kansas City permitted an allowable stress of 170 lb. per sq. in. (1.2 MPa)(2.8). Subsequently, the American Civil Engineers' Handbook(2.8) (1941) attempted to classify RMC according to the regularity and texture of rock used and thereby recommended a maximum safe compressive working stress for each class (see Table 2.1).

Table 2.1 Maximum safe working stresses (S.W.S.) for RMC in compression laid in portland cement mortar (1 part portland cement to 3 parts sand) recommended by Merriman(2.8) (1941). *"For rubble masonry in lime mortar about 50% of the preceding values should be used."*

Kind of rubble	S.W.S. (Pounds per square inch)	*S.W.S. (MPa)*
Flat or scabbled stones	250	*1.7*
Irregular stones (not scabbled)	200	*1.4*
Very irregular stones (field stones)	100	*0.7*

The American Civil Engineers' handbook(2.8) further recommends that the tensile strength of RMC should be ignored for the purposes of design computations but *"In the analysis of existing structures, where the mortar is found to be strong and adhesive, a tensile unit stress of 15 lb. per sq. in. (0.1 MPa) may be allowed for masonry laid in portland cement mortar, 10 lb. per sq. in. (0.07 MPa) for that in natural cement mortar and 5 lb. per sq. in. (0.03 MPa) for that in lime mortar"*.

2.7.2 Compliance with current codes of practice

It is difficult to justify the use of RMC in terms of present structural design codes. Only one modern code of practice (BS 5628 : Part : 1978 Structural use of unreinforced masonry)(2.48) appears to make reference to the characteristic strength of RMC.

"23.1.9 The characteristic strength of random rubble masonry may be taken as 75% of the corresponding strength of natural stone masonry built with similar materials. In the case of rubble masonry built with lime mortar, the characteristic strength may be taken as one-half of that for masonry built in mortar designation (iv)." The previous clause states:- *".... natural stone masonry should be designed on the basis of solid concrete blocks of an equivalent compressive strength."* Unfortunately, it appears to offer no guidance about how to reconcile the strength of regular stone blocks with solid concrete blocks and is therefore of limited practical value.

The concrete design code, SABS 0100 : Part 2[2.49], allows the use of plums in concrete with the following provisos:-

1) The minimum thickness of the concrete is to be 300 mm. (Most RMC structures are significantly thicker than this.)

2) The maximum size of plums must be 300 mm, or 1/3 of the concrete thickness. (The biggest boulders used in RMC today are typically not larger than this.)

3) There must be at least 75 mm of concrete between the plums. (This proviso cannot be ensured given the current method of RMC construction as it uses an extrudeable mortar rather than a stiff concrete as its matrix. Moreover, compliance here would necessitate a far greater proportion of costly cement.)

4) The strength of the plums must not be less than the strength of the coarse aggregate required by SABS 1083. (The abundance of geological variations within some localities and the sophisticated nature of the test make conformance with this proviso impractical if not impossible.)

5) The plums must not have any adhering coating or film which may reduce the bond to the concrete. (Compliance with this proviso would exclude the use of most naturally occurring colluvial material which is abundant and freely available throughout many parts of southern Africa and which has been used with success in numerous RMC structures.)

Thus, unfortunately it is not possible to comply with this code. However, it would be a pity if such non-compliance continued to preclude RMC from competing with traditional materials in more challenging future projects.

2.7.3 Evidence of an increasing dependence upon RMC strength

Figure 2.11 illustrates how typical profiles of RMC arch dams appear to have evolved. Much of the economy achieved by making the structures more slender may be attributable to improved methods of structural analysis but a significant proportion owes its existence to a growing dependence upon the material's strength. Chemaly[2.25] reports that Wild, who designed all the major RMC dams in Zimbabwe including Eirene Dam shown below, limits "average arch stresses" to 300 ton/m^2 (2.94 MPa) which he assumes to be roughly 25 % of the strength of the masonry. This is about three times higher than the allowable working stresses permitted by the American building codes[2.8] mentioned previously. Furthermore, Wild's "average arch stresses" do not include any thermal stress component. Wild[2.24] justifies this omission as follows:- "*...Zimbabwe is fortunate in that increased cantilever tensions due to a drop in temperature are unlikely to occur. Low temperatures never occur at the same time as high floods. In fact, the water temperature is likely to be not far from the temperature at grout jointing in most cases...*" This growing dependence upon the reserves of material strength does not appear to have been rationally justified. While the advent of modern portland cement has undoubtedly ensured more consistent and durable mortars, there is an apparent absence of physical evidence to confirm that RMC is really as strong as Wild assumes it to be.

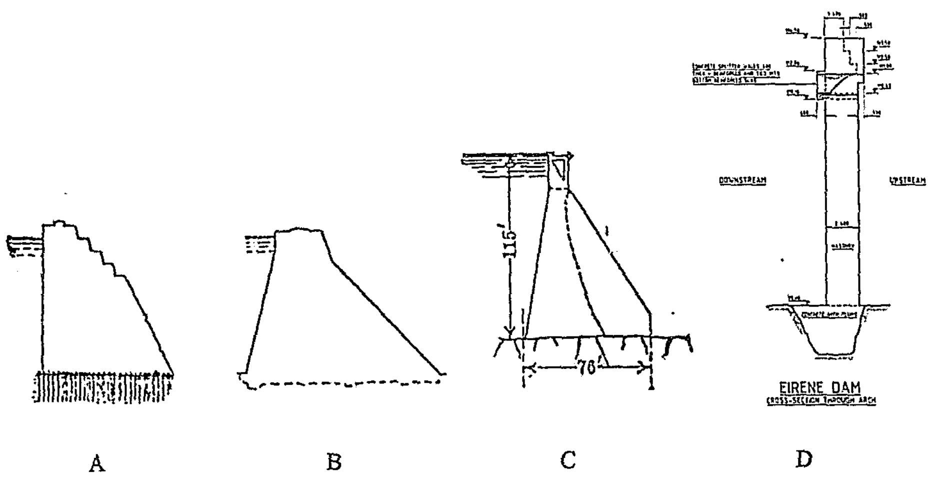

Fig 2.11 Profiles of typical RMC arch dams built over a century ago compared to a typical modern RMC structure. **A.** Puentes Dam, Spain, 1791, held water for ten years. In 1802 its pile foundation washed out and 608 lives were lost. **B.** Gillepe Dam, Belgium 1875. **C.** Sweet water Dam California 1888. **D.** Eirene Dam, Zimbabwe 1987.

2.7.4 Other references to the strength of RMC

Sims (1993)[2.9] appears to be the only author in recent times to have made reference to physical tests conducted on large specimens of RMC to determine its strength. Unfortunately, he cites no details and his sources of information could not be traced. He concludes that, ultimately, the strength achieved by mortars made of hydraulic lime and portland cement are not much different from each other, and not much less than cement concrete. Typically, "*they both reach a similar strength of about 30 MPa after two years. The tensile strength is about 5-12% of its compressive strength.*" (he does not specify the proportions of ingredients). Of consequence are their respective rates of strength development. "*The lime mortar sets considerably more slowly than cement, typically attaining a compressive strength of 15 MPa after 28 days*". Sims deduces (apparently from the data of others) that as the richness of the mortar is increased from a ratio of lime to sand of 1:5 to 1:3, that the strength of RMC is increased but that insignificant further benefit is derived if the mixture is made still richer.

In a more recent publication from India, Gopala Rao[2.21] has proposed the use of concrete instead of mortar as the "matrix phase" for RMC, a "new" material he calls '*masoncrete*'. This author is apparently unaware of cyclopean concrete, used by the Americans a century ago. He states that the strength of a unit of 'masonrcrete' will exceed that of an equivalent unit of RMC containing the same quantity of cement (he does not state by what margin). However, this statement lacks both theoretical support and experimental verification.

Hence, chapters three to five of this thesis will attempt to find answers to some of these questions to eliminate some of the uncertainties about the mechanical properties of RMC including its strength and behaviour under compressive load, its deformation behaviour and its response to temperature changes.

2.8 REFERENCE TO PRECEDENT

The American Civil Engineer's Handbook (revised 1941)[2.8], provides brief statistics of 144 masonry dams built throughout the world before that time. It reports numerous failures which account for thousands of lost lives, yet, no mention is made of any failure arising as a direct result of a geological material deficiency. Some of the geological materials successfully employed worldwide include[2.8]:- granites, gneiss, trap, syenite, limestone, sandstone, quartzite, porphyrite, linneite slate and crystaline marble. More specifically, in southern Africa, dolerite, quartz vein, weathered granite[2.44], foyaite[2.36,2.37], porphyritic biotite-granite[2.34] and basalt[2.35] have been used in the recent past. Most failures of RMC structures have been attributed not to insufficient compressive strength, but to factors such as foundation inadequacies[2.8,2.9,2.22,2.23,2.26-2.28] and gradual deterioration of the mortar matrix[2.9].

Unfortunately, few South African RMC structures appear to have benefited from the design and construction experience gained elsewhere. For example, South African designers of RMC arch bridges have not heeded basic lessons learnt by Zimbabwean engineers[2.22-2.28]. Zimbabwean methods of design and construction evolved empirically and by serendipity, often at the expense of entire structures being destroyed by floods, or being circumnavigated and rendered useless by obstinate rivers. Their experience can therefore provide a significant reference to spare other developing countries from making the same costly mistakes. Unfortunately, their valuable knowledge and experience has not been meticulously collated and disseminated. Consequently, many RMC structures continue to be built in other parts of southern Africa without the benefit of this experience. To date, only one South African designer[2.34] has recruited the expertise of experienced Zimbabwean designers and contractors. Others apparently believe that conditions in South Africa are so unique that lessons learnt elsewhere are of no value to themselves. The recommendations at the end of this thesis will therefore endeavour to collate previous experiences to compliment the raw research findings in a way that will hopefully be of benefit to future practitioners.

2.9 CONCLUDING SUMMARY

This literature survey has revealed that RMC does possess the potential to provide competent infrastructure and create labour-intensive employment for the unskilled without costing a premium. Historically, the competitive advantage of RMC appears to have emanated from RMC's low energy demand. Today, RMC's competitive advantage may be attributable to its efficient deployment of abundant local resources. However, RMC's future potential may be threatened by a lack of technical data required for rational design. The few references to the mechanical properties of RMC predate 1950, and appear unsubstantiated. As a result, structural engineers have been forced to base their designs on limited precedent alone. A study of the evolution of these RMC structures shows evidence of an apparently unjustified growing dependence upon the reserves of RMC strength. In addition, it has been shown that past experiences in building RMC structures in parts of South Africa will not necessarily apply elsewhere. The following chapters will therefore attempt to address this unsatisfactory state of affairs, starting with the exploration of RMC's strength, variability and failure mechanisms in Chapter 3.

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CHAPTER 3

STRENGTH, VARIABILITY AND FAILURE MECHANISMS OF RUBBLE MASONRY CONCRETE UNDER COMPRESSION

3.1 INTRODUCTION

Knowledge of a material's strength provides the basis for sound rational design. Without it, the designer has no idea of a structure's margin of safety against failure and the only available means of predicting the reliability of a new design is by reference to the precedent of another similar structure. Appreciation of a material's behaviour and variability under stress is equally important, since it enables the designer to assess the consequences of overload and apply an appropriate factor of safety to reduce the risk of catastrophe to an acceptable level without excessively compromising a structure's financial viability.

Ironically, in our advanced technical age, we still do not appear to have an adequate reference to the strength of Rubble Masonry Concrete (RMC), despite it probably being the oldest man-made particulate composite building material on earth. This lack of knowledge is most certainly due to the difficulty of testing a material of such coarse heterogeneous texture; a problem appreciated by engineers and geologists, throughout the world, who have wanted to measure the properties of natural conglomerates[3.1,3.2]. The strength of most other materials can be simply derived experimentally by dividing the load required to break small representative prismoidal specimens by the relevant cross sectional area of each specimen. However, to establish the mechanical properties of RMC requires extremely large specimens and heavy loading apparatus since its boulder inclusions are typically bigger than even the largest conventional test specimens.

Given the mechanical properties of the constituent phases, their volumetric proportions, distributions and orientations, it may one day be possible to deduce a particulate composite's mechanical properties. For example, Volpe, *et al.*[3.3] have suggested that the strength of a particulate composite can be represented by the weighted average of the strengths of the weaker matrix and the stronger inclusions, based on their volumetric proportions. However, such an attempt may produce serious discrepancies. An analogy between two elements and their chemical compound may be useful here. As is well known, when two elements combine to form a chemical compound, the latter acquires characteristic properties of its own which seldom bear any resemblance to either of the constituent elements. Thus, since this approach has no theoretical basis it would appear to be a far cry from practical reality. For the time being, results from large scale tests will probably yield more acceptable data.

Designers have been primarily concerned about this material's strength and behaviour under compression. Compressive strength is a property which is relatively eas verify and which is readily understood and accepted by designers and contractors alike. Furthermore, it has been argued that, since brittle materials essentially always fail in tension, regardless of whether their loading is compressive, shear or tensile, that data obtained from uniaxial compressive tests may also be used to gain an indication of their tensile properties and behaviour[3.4,3.5]. Therefore, the understanding of RMC's properties and behaviour under compression seemed an obvious point of departure.

3.2 FAILURE MECHANISMS IN CONCRETE AND NATURAL CONGLOMERATES

Before dealing with the specific case of RMC, it may be useful to review existing understanding of the behaviours of analogous materials such as conventional concrete and natural conglomerates. It is well established[3.6,3.7] that within particulate composites under a predominant load, localised "bond" stresses develop at the interfaces between the inclusions and the matrix to facilitate the transfer of load between the softer phase (usually the matrix) and the stiffer phase (usually the inclusions). The magnitude of these bond stresses depends on the difference in stiffness between the two phases and the extent of any discontinuity of the matrix-inclusion interface[3.6,3.7]. The softer more yielding matrix distorts to shed its load to the stiffer inclusions resulting in localised stress concentrations at the phase interfaces, within the inclusions and in the matrix between inclusions in the path of the principal stress. Newman[3.6] confirms this in his description of work done by Dantu[3.7], who measured localised strains on the surfaces of concrete specimens, under an applied uniaxial compression, by a photo-elastic technique. Dantu found that strains in the softer mortar phase were generally higher than those in the more rigid aggregate particles and that the maximum strain at the aggregate-paste interface was four to six times the average composite strain. The corresponding stress distribution, calculated from the elastic moduli of the two phases, indicated that the maximum stress in the aggregate was about 2,8 times the mean, whereas the maximum stress in the mortar was about 1,9 times the mean.

3.2.1 The effect of coarse aggregates on particulate composite strength

Conservative engineering practice has tended to limit particulate composite strength to that of the weaker matrix. Indeed, when working with bimrock (block-in-matrix rock) and bimsoils, it is universal engineering practice to design for the strength of the weaker matrix[3.8]. However, the question of whether a soft material (matrix) may be reinforced through the addition of particulate inclusions has resulted in the birth of a complex science. The hypotheses, experimental results and explanations of numerous researchers[3.2,3.9-3.14] who have pondered this question are difficult to reconcile and far from conclusive. Under particular circumstances, the addition of inclusions has been found to increase compressive strength, yet under others, inclusions are reported to weaken the composite. For example, using the 10% Fines Aggregate Crushing Test (10% FACT, SABS 842) as a measure of aggregate strength, Davis[3.9] investigated the relationship between aggregate strength and the compressive strength of concrete. He concluded that the compressive strength of normal structural-grade concrete, made with conventional South African concrete making aggregates (typically 10% FACT of 160 kN and over), was not significantly affected by the crushing value of the aggregate. However, as the strength of the concrete increased, the strength and surface characteristics of these aggregates assumed a greater significance. In the manufacture of very high strength concrete (80 MPa and over; water:cement ratios of 0.40 to 0.33), he found that strength and surface characteristics of aggregates become a factor, as evidenced by the mortar matrix component strength exceeding that of the concrete by 10% or more. Furthermore, Jones and Kaplan[3.10] studied the effect of adding coarse aggregate to mortar and found that for leaner mixes, the compressive strengths of concretes were usually greater than their pure mortar counterparts but that this was not necessarily so as the strength of the mortar matrix approached that of the aggregate. These findings may be partly attributable to fracturing of the aggregate as observed by Conjeaud *et al.*[3.11] and Cottin *et al.*[3.12] who have noted that as the strength of concrete increases, the fracture path increasingly begins to go *through* rather than around, the aggregate particles.

Okajima[3.13] has gone further and demonstrated that composite strength increases as the volume fraction occupied by particulate inclusions increases but adds the proviso that the stiffness of the inclusions must exceed that of the matrix. This is consistent with a similar test described by Addis[3.14] where the cube strength of concrete was reported to increase by 15% as the volumetric fraction of stiff aggregate was increased from 60% to 70%.

Beyond the immediate ambit of concrete, Lindquist and Goodman[3.2], in a study of natural melange[1*] behaviour, have noted that in order to afford the composite greater strength, the strength of the inclusion phase needs to exceed that of the matrix by a minimal margin. This conclusion followed a series of triaxial load tests on physical model melanges with the block (inclusion) and matrix phases made from cement-fly ash and cement-bentonite mixtures respectively so that the inclusions were only twice as strong as the matrix. In accordance with the observations of Okajima and Addis, the compressive strength of these melange specimens was found to increase as the volume fraction of the stiff inclusions increased. They attribute this increase to an increase in the internal angle of friction, consequent upon the failure surface becoming more tortuous (it has to fail around more inclusions) at higher inclusion proportions. However, below a threshold of 30%, the presence of inclusions appeared to have little effect on strength. This observation is consistent with the previously undemonstrated hypotheses of D'Elia, *et al.*[3.1] and Savely[3.15], of a minimum inclusion threshold for melange and conglomerate respectively. Evidence of a similar threshold has been observed in heterogeneous soils. Based on a review of soil literature and some of their own work, Irfan and Tang[3.16] have proposed a threshold volumetric inclusion proportion of 25% for heterogeneous soils. Finally, Lindquist and Goodman's results[3.2] also show that the orientation of the longitudinal axes of the inclusions with respect to the principal stress may have a profound effect on composite strength. In their case, the most adversely orientated inclusions had an inclination of 30^0 with respect to the principal stress and subsequently the lowest cohesion. This corroborates the assertions of Jaeger[3.17] and Donath[3.18], that anisotropic material should exhibit strength anisotropy.

Despite their triaxial nature, the phenomena shown to affect melange strength in Lindquist and Goodman's tests may also apply to man-made particulate composites such as RMC under 'uniaxial' load. Considero[3.19], Richart *et al.*[3.20] and Gardner[3.21] have all reasoned that any theory capable of predicting the behaviour of granular cohesive material can be applied to concrete. Therefore, they postulate the strength of concrete under triaxial stress may be equal to its 'unconfined' failure strength plus a constant times the confining pressure. However, it

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[1*] **Melange**: French word for a mixture of relatively large inclusions within a matrix of finer and weaker texture

should be borne in mind that, beyond some threshold, the confining pressure in a triaxial test will probably have the effect of improving the toughness of the mortar matrix by suppressing crack growth and making it behave as a ductile, rather than a brittle material. Nevertheless, assuming that these triaxial phenomena may be applied in a less confined case, it does not appear that large suspended aggregates require great strength to afford additional compressive strength to the composite, provided the strength of the inclusions is at least marginally greater than that of the matrix. The magnitude of this margin (to prevent failure through the inclusions) does not appear to have been accurately established and may be specific to individual cases. However, in Lindquist and Goodman's case a factor of only two proved sufficient.

3.2.2 The effect of size of inclusions upon compressive strength

From the cracked hulls of Liberty Ships, which broke at surprisingly low stresses, to the filaments (whiskers) of glass-fibre strands, which break at higher stresses as they get thinner, there are many examples that lead to the conclusion that material strength decreases as specimens get bigger(3.55). Concrete specimens (containing aggregates of a constant size, ie. not scaled in proportion to the specimen dimensions) appear to follow this law as evidenced by many researchers(3.22-3.25) who have discovered that the crushing strengths of small concrete cube specimens exceeded the strengths of their larger counterparts. Numerous authors(3.25-3.27) have also shown that the tensile strength of concrete decreases as the nominal coarse aggregate size increases. However, it will be shown that size effect phenomena do not necessarily apply in the case of an increasing nominal particle size in a predominantly compressive stress field.

The United States Bureau of Reclamation(3.25) and Walker and Bloem(3.26) used large scale cylinder tests (up to 48 inches long by 24 inches in diameter {1220X600 mm}) in an effort to explore the effect of maximum size of aggregate (up to six inches {150 mm}) upon the compressive strength of concrete used in structures such as Hoover Dam. Their results confirmed a relationship that for a given water:cement ratio, strength decreased as aggregate size increased. However, they noted that this phenomenon only became pronounced as the matrix became stronger, in which case, failure appeared to be initiated by a parting of the two phases at their interfaces. It seems reasonable to deduce that this relationship is probably only marginal for concretes other than high strength grades since other reports by Bloem and Gaynor(3.27) and Higginson *et al.*(3.28) conclude that the compressive strength of structural and lower grades of concrete is little affected by the size of stone used in the mix. Unfortunately, none of these studies provide satisfactory explanations. An increased proportion of entrapped bleed-water beneath the undersides of the larger aggregates, as noted by Hughes and Ash[3.29], is unlikely to have made a significant contribution to this weakening since cylinders are loaded parallel to the direction of casting and therefore perpendicular to planes of weakness created by bleed-water lenses.

Davis[3.9] argues that:- "*Large particles are responsible for high interfacial bond stresses owing to the limited surface areas available to accommodate bond forces* (to transfer load between phases). *Smaller sizes of aggregate, however, have greater specific surfaces and are therefore better able to transmit these forces.*" Presumably, Davis makes the assumption that the magnitudes of internal forces to be transmitted via these interfaces remain constant regardless of the nominal size of coarse aggregate. Hence, assuming this is true, it seems reasonable to speculate that aggregate surface phenomena, which may play a relatively minor role in affording strength to normal structural grade concrete (with relatively small aggregate), should become more critical when the specific surface area available for bonding with the matrix diminishes (as a consequence of using larger aggregate).

More recently, Baker[3.30] has cautioned against the indiscretionate application of relative size-scale effects to particulate composites and has argued that aggregate effects cannot be scaled.

> *"Increasing the nominal size of aggregate may be expected to affect the mechanical properties of concrete by: (1) influencing the development of micro-cracking (possibly as a consequence of higher interfacial stresses caused by a decreased surface area), (2) shielding the matrix by arresting or deflecting cracks, (3) making the failure "plane" more undular and (4) toughening the wake zone[2*]."*

Baker reasons that by increasing the particle size (assuming idealised spherical particles), the radius of curvature of the path which the crack is forced to follow is correspondingly increased. Theoretically, this would require less force to drive the interface crack and therefore decrease the apparent strength. However, in practice, with the exception of river rounded pebbles, aggregate particles are seldom round and spherical. The same sharp edges that occur as a result of the coincidence of fracture planes on small particles also exist on larger specimens of the same material. In short, sharp edges remain sharp, irrespective of scale. Thus, particulate composite materials are probably more sensitive to the curvature on the edges of these aggregates than their nominal particle size.

[2*] Wake zone: Zone of discontinuity in the "wake" of an advancing crack.

3.2.3 Relationship between the properties of the interface and the mechanical properties of the composite

The question of a direct link between interfacial bond strength and concrete strength has been a subject of much debate. Cracks in a heterogeneous material like concrete propagate in a direction which is near-perpendicular to the maximum tensile stress, but they also tend to follow the weakest path. Addis[3.31] has proposed that the strength of concrete at failure (albeit compressive) may be analogous to the weakest link of a chain. His chain has three types of link: aggregate, aggregate-paste interface and hardened cement paste; failure occurs when the weakest link fails. Conventional wisdom has it that the aggregate-paste interfacial zone is the 'weak link' in concrete[3.32-3.34]. Sabin (1905)[3.34] pointed out that "*since mortars are usually employed to bind other materials together, it follows that adhesive strength is of the greatest importance*". Certainly, it is common to see fracture paths in ordinary concrete predominantly routed along the interfaces between the coarse aggregate particles and the matrix. This may be due to an inherent weakness of the interface, or to stress concentrations at these interfaces, or perhaps a combination of these two phenomena.

Numerous studies[3.35-3.37,3.41,3.42] have concluded that certain desirable properties of concrete, including compressive strength[3.35], may be improved by increasing the interfacial bond strength. In practice, going from no bond to perfect bond, reported strength increases are not overwhelming but generally lie in the range of 15% to 40%, with improvements in tensile strength being more significant than those in compressive strength[3.39]. Using a model to simulate the stress distribution around a single stiff aggregate particle in a soft cement matrix, Vile[3.43] has postulated a most probable order of failure: (1) Tensile bond failure; (2) shear bond failure; (3) shear and tensile matrix failure; (4) occasional aggregate failure.

3.2.4 Summary

It would appear that the compressive strength of a particulate composite may be enhanced, beyond a minimum threshold, by the addition of inclusions which are stronger and stiffer than its matrix phase, provided a mechanism to transfer some minimum load between the phases exists. The phenomena affording this strengthening probably include the shielding or arresting of advancing cracks within the matrix, increased tortuosity of the failure surfaces (caused by the obstruction imposed by the inclusions) and toughening of the wake zone, as a result of the mechanical interlock formed by the undulating fracture surface. These effects vary with inclusion size although not necessarily in compliance with existing size-scale effect theory.

3.3 EXPERIMENTAL EXPLORATION OF RMC

3.3.1 Testing philosophy

As mentioned above, the properties of particulate composites may be influenced by the size of their particulate inclusions - a relationship not necessarily compliant with existing size-scale effect laws. Therefore, there appears to be little scope for testing small physical models coupled to real specimens via scaling laws. Instead, the testing of full-scale representative specimens appears to be the only sure means of exploring this material's physical behaviour.

RMC is probably the coarsest heterogeneous construction material ever used by man; and such is the nature of coarse heterogeneous materials that they tend to exhibit much variability of mechanical properties. Thus, ideally conclusions need to be drawn from averaged data derived from large populations for each control variable tested. Unfortunately however, the very high cost of material transportation, mould fabrication, load press rental and rubble removal, to test such large specimens, makes this prohibitively expensive. Therefore, it is imperative that the testing strategy be contrived to derive maximum experimental data. Furthermore, it is prudent to first explore the extremes of control variables rather than attempt to measure subtle 'nuances', since the latter may well be obscured by the material's high variability. The tests which follow were configured with this philosophy in mind.

The following control variables are explored in this chapter:-

- Nominal inclusion size
- Surface bonding characteristics
- Orientation of the longest inclusion axes with respect to principle stress
- The relationship between matrix strength and composite strength

3.3.2 Choice of testing technique

Traditional test cubes cannot accommodate even the smallest boulders used in RMC and are therefore inappropriate. A comprehensive literature search explored the possibility of adopting some precedent to measure the strength of RMC. Unfortunately, there appears to be no record of any testing performed on a material with such large inclusions. Chamaly[3.44], has advocated testing "undisturbed" samples of RMC, to be obtained by coring the hearting masonry of dams, in an effort to establish its true character and strength in service. However, coring poses several practical difficulties. For example, the drilling resistance of each phase would be significantly different, possibly causing the harder material to become detached from the weaker matrix, thereby weakening the specimen sufficiently that it may lack the necessary tenacity to survive extraction. Furthermore, the costs of coring representative samples of RMC would be prohibitive, due to the coarseness of its texture necessitating very large core diameters. Consequently, a method of testing RMC was developed to explore and possibly quantify phenomena which afford RMC compressive strength(3.45).

3.3.3 Pilot study

A pilot study(3.48) (see Appendix 1) was undertaken to gain a preliminary indication of the behaviour of RMC under compression and to explore a suitable procedure for further testing. As the order of strength of this material and the maximum size of its inclusions were unknown quantities at that time, three cubic specimens of different sizes were cast (300 mm, 400 mm and 500 mm) with the intention of adopting the smallest size possible (the most convenient to handle) for further tests. Cubic shape specimens were chosen because they optimally utilise available platen area and because they can be cast in plywood moulds which are affordable and easy to build. The specimens were cured in their moulds, indoors to preclude thermal damage, for 28 days before testing. The test results are presented in Table 3.1. The 28 day strength of the mortar matrix (derived by crushing 100 mm cube specimens) was 14,93 MPa.

Table 3.1 RMC strengths measured in the pilot study(3.48).

Cube Size (mm)	28 day Strength (MPa)
300	14,0
400	9,0
500	9,6

During the placement of the RMC into these moulds, it became immediately apparent that the 300 mm and 400 mm cubes were unable to accommodate the bigger boulders (therefore they cannot be representative of RMC). Furthermore, the large size of boulders in relation to the size of the moulds influenced the particle packing, particularly in the two smaller sizes. This phenomenon, known as the "wall effect", alters the natural inclusion volume fraction and may affect the specimens' strength(3.56). Existing standards(3.49,3.57-3.59) limit the size of test specimens in relation to the maximum size of aggregate (typically from three(3.57) to five(3.58,3.59) times the nominal maximum size of the aggregate) to limit this wall effect. Even the largest 500 mm RMC cube tested, violated this limitation, yet, this size was the [illegible] which could be accommodated within the platen area of our biggest hydraulic press. M[illegible] ll force, this press could not crush 500 mm specimens if they were stronger than 2[illegible] ikely possibility but a possibility nevertheless. Furthermore, weighing abo[illegible] kg, the 500 mm specimen size bordered the threshold of manageability, given the available resources. Nevertheless, the 500 mm cube size was subsequently adopted for all further uniaxial strength testing although had it been possible to test even bigger specimens, this would have been preferred.

The high strength of the 300 mm specimen may be attributable to the wall effect as well as the fact that it was not truly representative of RMC since some of its boulder inclusions were broken to enable them to fit into the small mould.

3.3.4 Development of a proposed test for exploring parameters governing the behaviour of RMC loaded in uniaxial compression

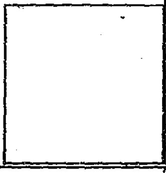
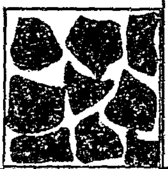
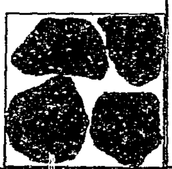
Based on the testing experience from the pilot study, trials with other specimens and a review of literature on the development of conventional concrete compression testing, a procedure for testing RMC was developed. A comprehensive description of this proposed test method and its evolution is presented elsewhere[3.45] (see Appendix 2). In essence, the test utilises 500 mm cubic specimens to accommodate the largest boulders typically used (even though much larger specimens would have been preferred). Parameters which might influence the apparent compressive strength, such as geometric tolerances of forms, platen texture and speed and concentricity of loading are standardised to enhance repeatability and reproducibility.

3.3.5 Testing of cubic test specimens to explore the effects of increasing inclusion size

Fifteen, 500 mm cubic specimens were cast and tested in accordance with the abovementioned procedure[3.45] to explore the effect of inclusion size on the strength and variability of RMC in compression. Quarried Olifantsfontein dolomite with clean, freshly fractured surfaces was collected, sorted and stockpiled into three size fractions according to particle mass. The smallest fraction (1 to 4 kg) was chosen to border the threshold of the minimum size typically used, the intermediate fraction (7 to 15 kg) represented a size that felt most comfortable to handle and the largest fraction (25 to 40 kg) was selected to border the upper threshold typically used in practice. A transit-mixed batch of collapse slump mortar with a W:C ratio of 0.84 (portland cement content of 357 kg/m^3 without extender) and crushed dolerite sand (FM>3) was delivered to ensure consistency of the matrix. A series of 100 mm test cubes was cast to establish the conventionally derived mortar strength and also to establish the size-scale effect of the large specimens. The fifteen 500 mm cubes were divided into five series of three specimens per series. The first series of three 500 mm cubes was cast with pure mortar (without any inclusions) to establish the size scale effect and matrix variability. The second, third and fourth series contained inclusions of the smallest, intermediate and largest fractions of rock respectively. The fifth series contained inclusions of the largest and the smallest fractions of rock packed in such a way that the smaller particles occupied some of the interstitial volume between the larger particles as is now the custom in southern Africa. Cubes were packed by helpers who were instructed to maximise the content of stone and minimise the air voids. Thereafter, the specimens were cured in their moulds (indoors to limit thermal shock) and tested after 28 days on the same 500 tonne press used during the pilot study (shown in Figure 3.1). The results are presented in Table 3.2.

Fig 3.1 A 500 mm RMC specimen (weighing approxitately 300 kg) undergoing a compressive test under the 500 tonne Amsler press at the University of the Witwatersrand.

Table 3.2 Test data of fifteen, 500 mm cube specimens. Relative surface areas are relative to the interfacial surface area of the series containing the largest inclusions and are therefore dimensionless. Specific surface areas were calculated assuming a shape factor of two. (ie. Assuming the dolomite inclusions had surface areas twice as large as single equivalent spheres of equal volume).

Series	Single equivalent nominal particle Vol. (dm^3) & (Diam. mm)	Specimen number & Statistical data	Strength (MPa)	Volume fraction of rock (%)	Relative surface area (dimension-less)	Estimated surface area of inclusions (m^2/m^3)
1 		1	9,240	Nil		
		2	9,164	Nil		
		3	9,340	Nil		
		$\bar{x}$	9,25		-	-
		σ	0,09			
	No Rock	$\sigma/\bar{x}$	0,95%			
2 		4	10,024	41,4		
		5	10,088	42,0		
		6	10,228	42,4		
		$\bar{x}$	10,11	41,9	2,34	42
	0,9 dm^3	σ	0,10	0,5		
	(120 mm)	$\sigma/\bar{x}$	1,03%	1,2%		
3 		7	13,940	41,4		
		8	12,808	45,2		
		9	12,768	39,6		
		$\bar{x}$	13,17	42,0	1,44	26
	3,9 dm^3	σ	0,67	2,9		
	(195 mm)	$\sigma/\bar{x}$	5,05%	6,8%		
4 		10	14,088	39,7		
		11	14,404	40,6		
		12	12,600	46,4		
		$\bar{x}$	13,70	42,2	1	18
	11,6 dm^3	σ	0,96	3,6		
	(281 mm)	$\sigma/\bar{x}$	7,03%	8,6%		
5 		13	11,328	56,4		
		14	15,680	57,3		
		15	10,648	49,8		
		$\bar{x}$	12,55	54,5	1,3	24
	11,6 & 0,9 dm^3	σ	2,73	4,1		
	(281 & 120mm)	$\sigma/\bar{x}$	21,75 %	7,5%		

Notation	28 day 100 mm mortar cube strengths (MPa)	
	1)	15,07
$\bar{x}$ = mean	2)	14,84
σ = standard deviation from the mean	3)	14,74
$\sigma/\bar{x}$ = coefficient of variation from the mean	$\bar{x}$	14,79
expressed as a percentage of the mean	σ	0,3
	$\bar{x}/\sigma$	2,0%

3.3.6 Observations

A comparison of the volume fractions of rock inclusions (expressed as percentages in table 3.2) shows consistency at around 42% in the case of specimens containing single size aggregate fractions. This consistency provides a basis with which to isolate the effect of inclusion size without concern for the need to account for possible extraneous phenomena as a consequence of different inclusion volume fractions. Noteworthy observations are listed below.

1) The extremely small variation of the 500 mm mortar cube strengths ($\sigma/\bar{x} < 1\%$) provides some assurance of the consistency of the mechanical properties of the matrix.

2) The reduction in apparent strength as a result of size effects phenomena (and different testing machine characteristics) appears significant; the mean 500 mm mortar cube strength is less than two thirds of that of the 100 mm mortar cubes.

3) The incorporation of rock increased the strength without exception by between 9% and 48% (based on statistical analysis of averaged strengths).

4) In series 2 to 4, the mean composite strength increased as the nominal size of rock inclusion increased.

5) In series 2 to 4, the variation in strength within each series increased as the nominal size of rock inclusion increased.

The possibility that the 500 mm mortar cubes may have exhibited lower strengths due to thermal cracking (as a consequence of their size and higher cement contents evolving greater exothermic heat) appears extremely unlikely. FitzGibbon[3.60] has shown that the cracking strain of concrete is reached only when an internal thermal differential of 20 ^{0}C is exceeded. Using FitzGibbon's "worst case" model, the maximum possible temperature rise of the 500 mm mortar specimens could not have exceeded 16 ^{0}C (based on a cement content of 350 kg/m^3). Moreover, other factors mitigate this most pessimistic temperature difference. Firstly, the dolomite aggregate used is an excellent conductor of heat, exhibiting a thermal conductivity of about 3.3 J/m^{2}s°C/m[3.61] (in a spectrum ranging from expanded shale (0.85 J/m^{2}s^{0}C/m) at the low end to quartzite (3.5 J/m^{2}s^{0}C/m) at the high end). Secondly, the specimens were all cast under overcast conditions when ambient temperatures were less than 20 ^{0}C. Thirdly, the specimens were insulated against thermal shock (temperature drop) as they were cured indoors, in their moulds under polyethylene sheets.

Typical sequence of events leading to the disintegration of RMC under compression

A generalised sequence of events leading to the disintegration of specimens was noted in all testing to date. Initially, RMC appears to exhibit symptoms of distress similar to conventional concrete. At a load of between 70% and 90% of maximum, visible hairline cracks running sub-parallel to the principal stress appear. As the load increases to maximum, these cracks widen and coalesce with other cracks. At this stage, the widest cracks tend to form near to the edges and often an entire edge of mortar will become detached as shown in Figure 3.2. Examination of these detached mortar surfaces reveals almost clean breaks (often a slight grey discolouration is left on the rock surfaces) between the rock face and the matrix, indicative of tensile or shear bond failure.

Fig 3.2 Typical vertical crack parallel to the principal stress at about maximum load.

Beyond maximum load, the specimens usually disintegrate in the classic hourglass shape, analogous to the failure of a concrete cube. However, as previously mentioned, the rock inclusions in RMC frequently bear contiguously upon their adjacent neighbours. In specimens containing the largest size boulders (with the exception of those containing the weakest mortars (about 4 MPa) tested by Roxburgh[3.46]), these points of contact caused a considerable amount of rock fracturing in bearing. Conversely, almost no fracturing was observed in specimens without large inclusions (ie. specimens containing only the smallest boulders). The shattering of large contiguously placed boulders, due to bearing stress concentrations, was often audible and the effects are illustrated by Figures 3.3 and 3.4.

Fig 3.3 Fracturing of rock caused by very high local stresses as a consequence of boulders bearing against one another at points of contact. Left quartz vein. Right Olifantsfontein dolomite.

Fig 3.4 Fragments of the same quartz vein rock illustrated in Fig 3.3 showing the extent of fracture.

3.4 DISCUSSION

3.4.1 Variability

Comparison of the coefficients of variation within the first four series of tests (presented in Table 3.2) confirms that variability of both inclusion volume fraction and strength increases as inclusion size increases. This is to be expected as a consequence of testing a constant volume of an increasingly coarse and heterogeneous material since the bias evolved by a particularly favourable or unfavourable orientation of a single inclusion is more likely to distort the experimental outcome as the number of inclusions per specimen decreases. Therefore, the coefficients of strength variation in the fourth and fifth series are likely to be exaggerated and conservative. If the ratio of specimen size to inclusion size was increased, more realistic (lower) variations in strength could be expected. Nevertheless, these four recorded values are all low and acceptable within the range normally designated for concretes[(3.50)].

An anomaly is the disparity between the coefficient of variation of the fourth series (7%) and the much higher coefficient of the fifth series (22%); more than a threefold increase. To date, a satisfactory explanation for this has not availed. This is unfortunate since the fifth series is the one most representative of the constitution of RMC used in practice. Furthermore, these specimens were cast under idealised conditions from a single batch of mortar to eliminate the influence of as many extraneous factors as possible. RMC cast on site is likely to depend on mortar which has been crudely batched, with little or no control of its W:C ratio. Therefore, in practice, even higher variability may be expected. Roxburgh[(3.46)] reports the results of nine tests by the same testing procedure[(3.45)] in a parallel study. These specimens were cast under adverse circumstances during the final stages of construction of a Dam in Mpumalanga, South Africa. The stockpile of rock was contaminated with mud and heavy rain flooded the works, making control of the mix's water content between batches difficult. The corresponding coefficient of strength variation recorded between three specimens in a series was 30%.

3.4.2 Surface phenomena

As discussed previously, interfacial bond and coarse aggregate size are not deemed to contribute overwhelmingly to the compressive strength of conventional concrete. In the case of aggregate size, this may be because the increase in specific surface area (the total inclusion-matrix interfacial area in a given volume) is not exponentially affected by changes in nominal inclusion size. The specific surface area of a given volume of particles increases in linear proportion to particle length. Thus, by halving the linear dimensions of a given volume of particles their specific area doubles. On the corollary, we need to reduce the particle volumes of granular materials by 8 times just to double the specific surface area. This is illustrated in the context of a cube in the example in Figure 3.5, but is true regardless of particle shape, provided the material retains its fractal nature.

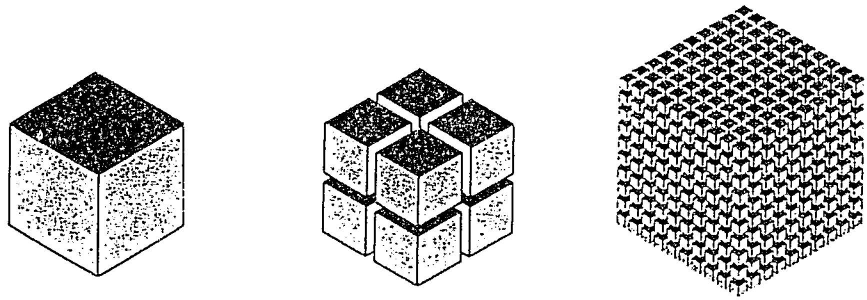


Fig 3.5 The linear relationship between particle size and surface area. A cube 1 m long exposes a surface area of 6 m^2 (A). Dividing this 1 m cube into eight smaller cubes, each with linear dimensions half as big as the former, doubles the surface area to 12 m^2 (B). Dividing it into 1000 smaller cubes (C) each with linear dimensions a tenth as big (compared to A) increases the surface area by one order of magnitude. Although the model illustrates the phenomenon in the context of cubic particles, the relationship holds true, regardless of shape, for all materials exhibiting a fractal nature.

Table 3.2 illustrates this relationship for the case in point. The estimated specific surface (the area of the inclusion-matrix interface in 1 m^3 of RMC) was calculated by multiplying the surface areas of the appropriate number of equivalent spherical volumes (that is equivalent to the known nominal volumes of the three size fractions used), by a shape factor of two. The number two is probably realistic of the dolomite in question but is insignificant in the outcome of this argument since only the relative relationships are important. By assigning a relative surface area of one to the composite containing the biggest nominal particles (11,6 dm^3, in series 4) as a basis for comparison, we see that a more than twelve-fold volumetric decrease (to 0,9 dm^3) is needed to increase the relative surface by only 2,34 times. Extrapolating this relationship, to the size of aggregate commonly used in concrete (say 19 mm), we see a significant difference in relative surface areas (19 mm aggregate has a surface area about 15 times larger than the reference 11,6 dm^3 fraction), and at least ten times the surface area of conventional RMC (consisting of big and small inclusions). Therefore, if interfacial bond stresses did increase in inverse proportion to the decreasing specific surface area (as the particle size increased), then the strength of RMC should be less than its equivalent concrete strength by about one order of magnitude. The reason that this is not the case, is because bond failure is a tension-shear type failure and the area of such a fracture surface is not much affected by aggregate size, as illustrated by the path lengths of the two hypothetical fracture surfaces in Figure 3.6. Assuming the composite in question consists of cubic particles with weak links at their joint surfaces, then it is of no consequence to the path length (from A to B) whether the particles are big or small. However, the more undular surface may be better able to resist sliding.

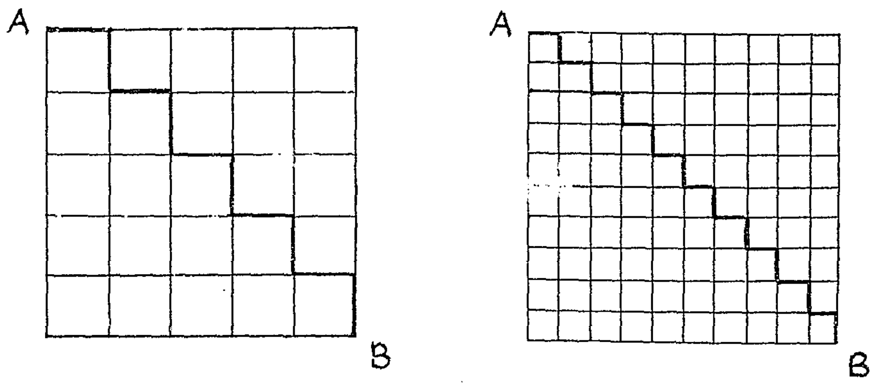


Fig 3.6 Hypothetical models representing parts of an infinite matrix containing regular cubic particles. Assuming tension-shear failure only occurs at the "weak link" joints, it can be seen that the fracture length from A to B is independent of the particle size.

Notwithstanding this fact, interfacial bond in RMC is probably more critical than in conventional concrete. Firstly, there is likely to be a greater inherent tensile stress (caused by factors such as dessication shrinkage and thermal strains) within the mortar matrix between inclusions since these mortar volumes become greater as the nominal particle size increases while the inclusions remain rigidly held because of their contiguity with adjacent neighbours. Secondly, any bond discontinuity, between phases, will affect a relatively large area, thereby placing greater stress on the adjacent continuity. Examples of phenomena which have been observed to inhibit good interfacial bonding in RMC include:-

1) **Lense-shaped cavities formed due to the entrapment of bleed-water as it becomes trapped against the undersides of large particles** (see Figure 3.7). In severe cases, the migration of bleed-water may also interrupt the bond at the sides of particles. In such cases the mortar surface near the interface exhibits a glassy appearance.

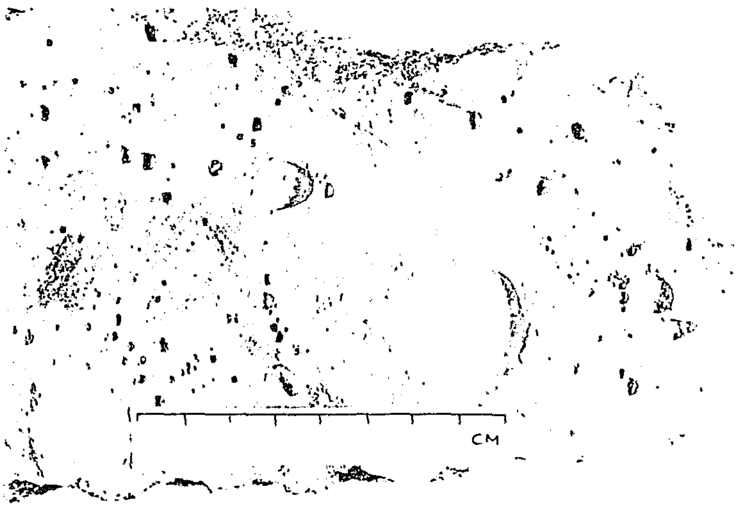


Fig 3.7 The upper surface of a layer of mortar de-bonded by a lense of bleed-water trapped against a flat horizontal under-surface of dolomite rock. Large stones are more inclined to trap bleed-water on its upward migration to the surface, particularly if their lower surfaces are horizontal or cupped. The presence of the lenses effectively de-bonds the phases at their interface.

2) **Powdery substances which form on the surfaces of some igneous rocks** (such as basalts, dolerites and gabros) as a result of their chemical weathering. The products of this chemical weathering include clays which preclude the paste from bonding with the coherent underlying rock surface. An indication of the extent to which this poor bond can reduce composite strength may be evidenced by comparing strengths from the pilot study (Table 3.1) with the fifth series in Table 3.2. The specimens in Table 3.2 contained freshly quarried rock with excellent bonding characteristics whereas those of the

pilot study (Table 3.1) contained an assortment of hand-gathered colluvium including a large proportion of dolerite. The surface of this dolerite had chemically weathered and developed a powdery skin containing illite and montmorillonite clays which could be rubbed off with finger pressure and which felt slippery when wet. Fracture of the specimens containing this weathered-skin-dolerite seemed to be initiated by bond failure at these powdery interfaces at a very early stage and the dislodged boulders appeared to have suffered much less distress than the other rock types. In many instances, remnants of this powdery surface remained in the cavities of the matrix after the stones had been dislodged as illustrated in Figure 3.8.

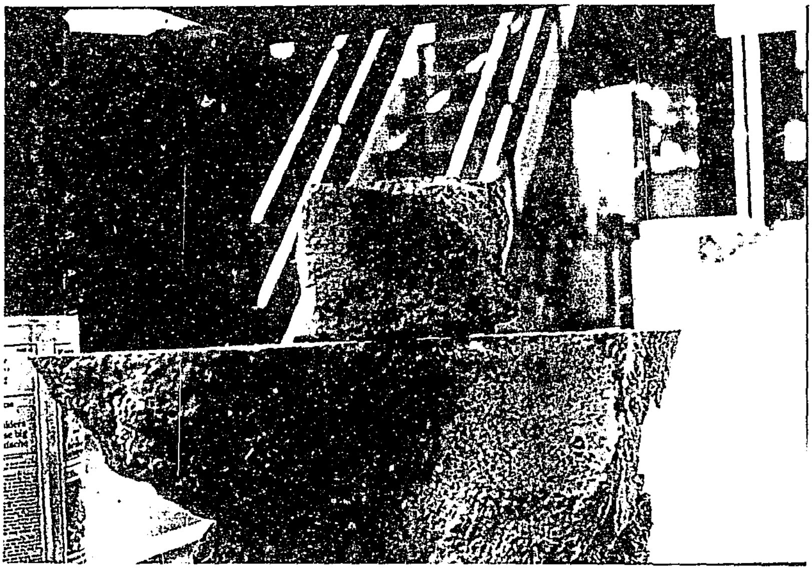


Fig 3.8 The dolerite boulder sitting on the cube became detached at low stress as a result of poor bonding characteristics with the matrix. Dolerite weathers chemically into illite and montmorillonite. This is undesirable because it forms a weak powdery substrate which inhibits a strong bond between the matrix and the sound underlying rock. The poor adhesion may be evidenced by a mustard coloured, powdery residue now attached to the cavity left in the mortar matrix.

3) **The contamination of any sound surface by dirt.** This usually occurs by rain water splashing mud against rocks in contact with the ground and the consequences are illustrated by Figure 3.9.

Fig 3.9 A lack of adhesion to sound, freshly quarried granite caused by contamination with mud.

3.4.3 Orientation of rocks

That anisotropic rock exhibits anisotropic mechanical properties, appears to be well recognised in rock mechanics[3.2,3.17]. RMC is inherently anisotropic due to the natural tendency for flat and/or elongated inclusions to lie horizontally. Elongated rocks which are orientated parallel to the principal stress axis tend to split the matrix apart by a cleaving and wedging action (see Figures 3.10 to 3.12). Conversely, it might be anticipated that similar shape rocks, orientated orthogonal to the principal stress, may be effective in tying the matrix together.

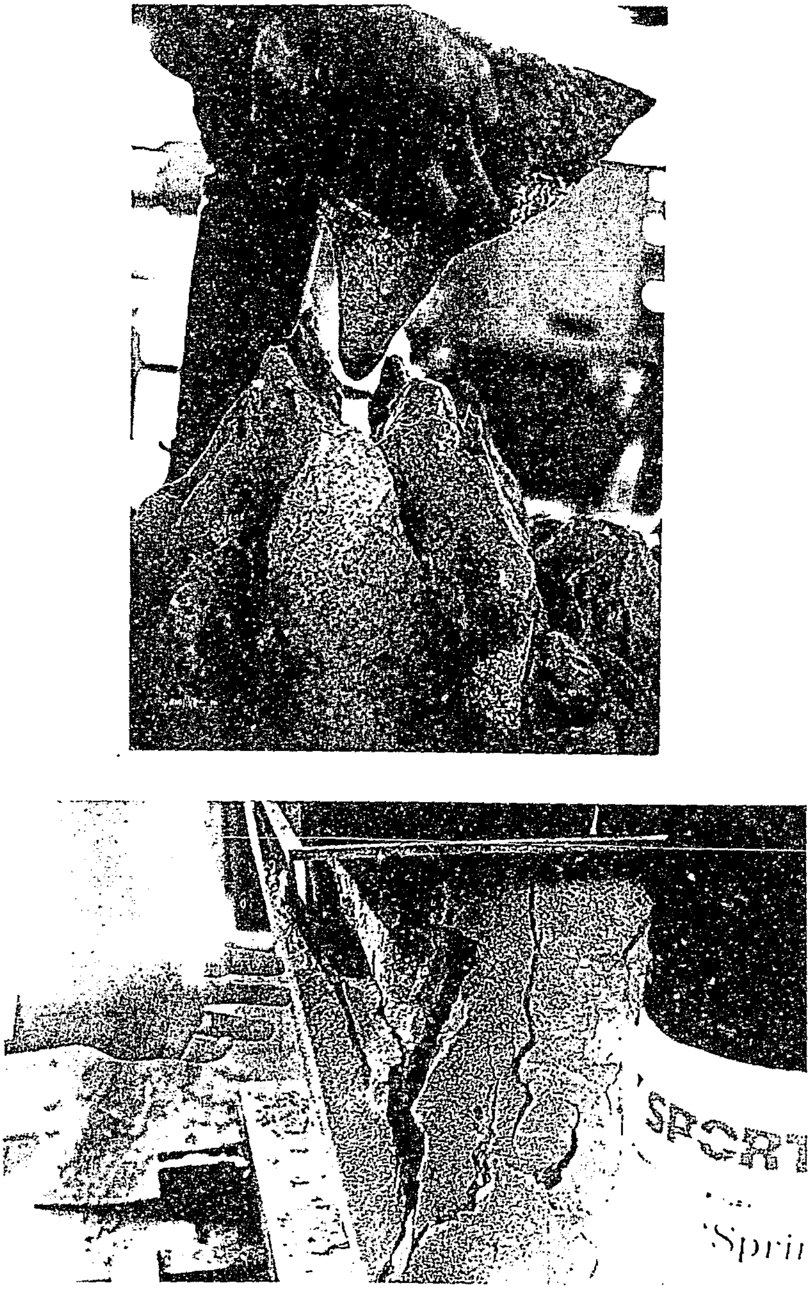


Fig 3.10 Typical wedging-cleaving failures caused by sharp inclusions orientated parallel to the principal stress.

In an effort to observe how different shaped inclusions precipitate fracture, two idealised brass inclusions were cast suspended in the centre of a transparent polyester cube. The inclusions were machined into equivalent cones in such a way that although their angular proportions were very different, their surface areas were identical (see Figure 3.11). Once the polyester had solidified, the two specimens were loaded in tandem (one on top of the other), parallel to both cones' longitudinal axes. As anticipated, the specimen containing the more slender cone, with sharper points, precipitated the first fracture surfaces, sub-parallel to the principal stress, radiating away from the inclusion. However, before the crack could be photographed, this specimen exploded violently. The experiment was repeated with near frictionless polyethylene platen surfaces and a transparent safety barrier. This time both specimens exploded simultaneously and ruptured the barrier. In the interests of safety, further testing with this brittle polyester matrix was aborted. Tougher high clarity (transparent) epoxy resins have subsequently availed but their high cost makes their use difficult to justify in this instance.

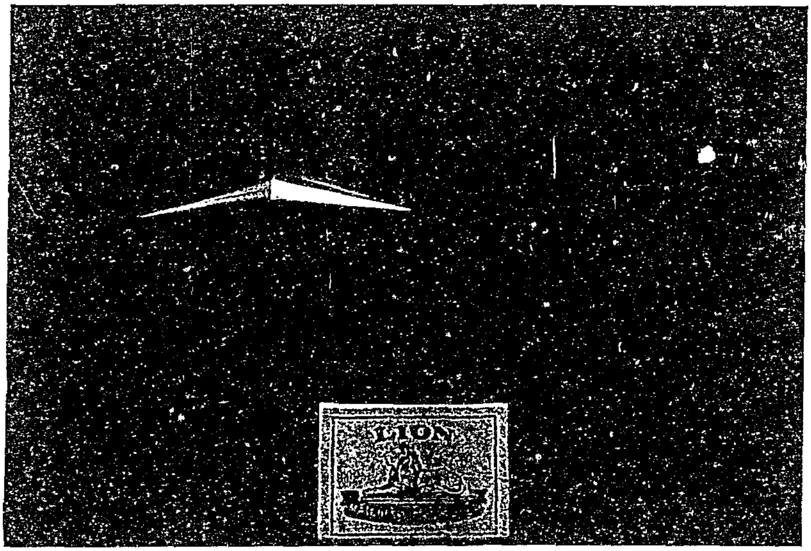


Fig 3.11 Different shaped inclusions modelled as equivalent cones in brass; both with equal surface areas. These cones were cast, centrally suspended in a transparent polyester matrix, and then loaded in tandem, parallel to their longitudinal axes. The more pointed cone precipitated the first fracture, sub-parallel to the principal stress, but shortly thereafter exploded, discharging the matrix as shrapnel.

Figure 3.12 shows a simplified schematic representation of post-bond equilibrium forces of such an idealised conical inclusion. The radial splitting component increases as:-

1) the angle β decreases since the inclusion wedges the matrix apart with greater leverage and/or
2) the coefficient of friction at the matrix/inclusion interface decreases and/or
3) the ratio of stiffness between the inclusion and the matrix increases

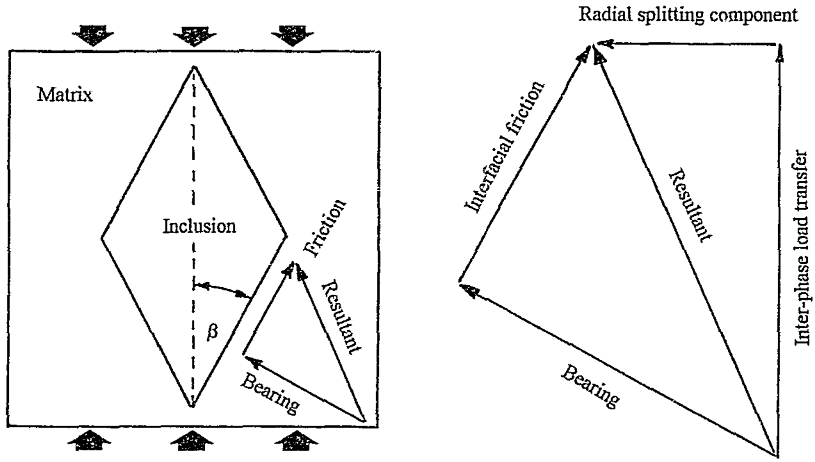


Fig 3.12 Simplified schematic representation of post-bond equilibrium forces around an idealised axially symmetrical suspended conical inclusion.

3.4.4 The contribution made by mortar matrix strength

Sims[3.52] has stated that as the richness of a lime mortar increases from a ratio of lime to sand of 1:5 to 1:3, that the strength of RMC is increased, but that insignificant further benefit is derived if the mixture is made still richer. This appears to have been corroborated by Roxburgh[3.46] who explored the relationship between matrix strength and RMC composite strength using portland cement mortars and freshly quarried granite (see Table 3.3). In the case of low strength mortars (4 to 5 MPa), he found that the measured strength of the RMC specimens was about the same as the measured strength of their 100 mm mortar cube counterparts. In cases of higher strength mortars (16 to 18 MPa), the measured RMC strength was only about 60% of the strength of the 100 mm mortar cube counterparts. Thus, at higher mortar strengths, the effect of a change of mortar strength on composite strength, was less significant than at low mortar strengths. Unfortunately, Roxburgh was unable to explore material with a crushing strength greater than 20 MPa, because until recently, available equipment has not been capable of testing 500 mm cubes which are stronger than 20 MPa.

Table 3.3 The effect of mortar matrix strength upon RMC composite strength from the extremes tested by Roxburgh(3.46).

	STRONG MORTAR		WEAK MORTAR	
	500 mm RMC cube strengths (MPa)	100 mm mortar cube derivatives (MPa)	500 mm RMC cube strengths (MPa)	100 mm mortar cube derivatives (MPa)
				4.0
	11.3	16.4	4.8	4.7
	12.7	16.5	4.1	4.1
	12.5	15.8	4.4	4.4
$\bar{x}$	12.2	16.2	4.4	4.3
σ	0.76	0.38	0.35	0.32
$\sigma/\bar{x}$	6.2%	2.3%	8.0%	7.4%

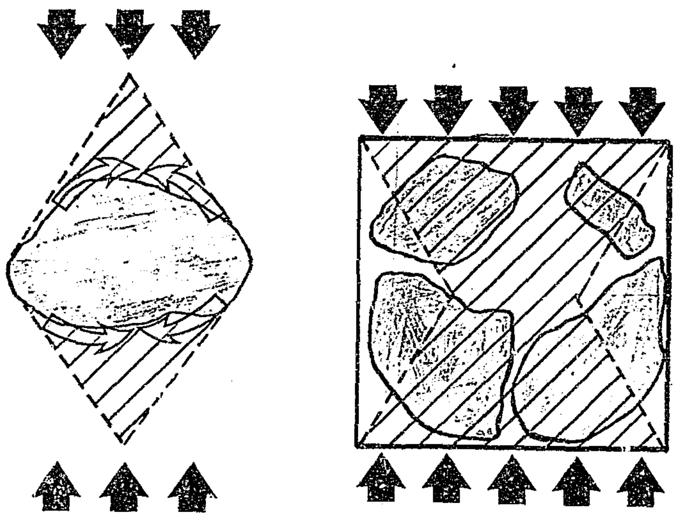
3.4.5 Relative size considerations

Increasing the size of inclusions within a given volume, either in a specimen or in a structure, has both positive and negative implications concerning the composite's compressive strength. Table 3.4 presents a list of some of these effects. The relative significance of the different effects may depend upon specific individual circumstances.

The most significant effect, as evidenced by this initiative and work by Bazant(3.53), is the ratio of specimen size to inclusion size. Large incl[illegible]nfine greater volumes of mortar by way of frictional constraint as shown in Figure 3.13a. [illegible]ubic test specimens, large inclusions afford confinement to the dilating matrix, particularly if part of them is embedded in the triaxially confined zone shown as a shaded area in Figure 3.13b. In a limited volume, such as a test cube, this may add significantly to the constraint already offered by the platens. This is why concrete testing specifications[3.49,3.54] limit the ratio of aggregate size to specimen size to a maximum. Unfortunately, limitations in available testing equipment have made compliance with this requirement impossible in testing RMC to date. To date, the biggest inclusions tested had a nominal diameter more than half the size of the cubic specimen length. Thus, this large-inclusion confining effect is probably responsible for a substantial proportion of the apparent strength gain between series two and four. A future project might aim to quantify this strengthening effect by comparing the measured strength of another similar series of specimens, containing the same size fractions, but loaded against near-frictionless platens. Alternatively, if significantly larger testing facilities avail, the size of specimens could be increased to comply with conventional concrete testing constraints. However, for the time being, it would be prudent to assume that RMC may, at best, be only slightly stronger than its mortar matrix and that its properties may be highly variable.

Table 3.4 A list of phenomena which may affect particulate composite strength as the size of the inclusions increase.

	Strengthening Effects		Weakening Effects
1)	Greater confining potential within a small volume	1)	Higher contact stresses as an inverse function of the number of rock contacts per unit volume
2)	Increased tortuosity of the failure surfaces resulting in a more undular wake zone with deeper interlock to better resist shear and sliding	2)	Greater entrapment of bleed-water by larger obstacles
3)	Greater capacity to shield and arrest advancing cracks	3)	Less surface area for interfacial bond
4)	Lower density of "weak link" critical flaws and potential crack initiation interfaces	4)	Less energy is required to drive cracks around the larger radii of ideal rounded particles
		5)	A greater number of flaws exist within the rock inclusions



(a) (b)

Fig 3.13 Triaxially constrained areas as a result of friction between the matrix and the inclusion surface (a). Triaxially confined zone (shaded) within a test cube which may anchor portions of large aggregates projecting beyond it into the "unconfined" zone (unshaded) (b)

3.5 CONCLUSIONS

1) The physical behaviour of particulate composites has been shown to be influenced by the size of the particulate inclusions in a way that does not always appear to comply with existing 'size-scale effect' laws. This was confirmed during the testing of 500 mm specimens when large boulders bearing upon one another fractured as a result of these high bearing stresses. Such fracturing was not observed in 500 mm specimens containing only the smallest boulders (ie. without any of the largest boulders). Therefore, the testing of full-scale representative specimens appears to remain the only reliable means of exploring RMC's physical behaviour.

2) The variability of cubic RMC specimen properties, containing uniform size inclusions, appears to be a function of their heterogeneity, expressed as the ratio of nominal inclusion size to specimen size. Although strength appears to increase significantly with increasing inclusion size, it is likely that this phenomenon arose predominantly as a consequence of the relatively small specimen size. Consequently, unless satisfactory evidence to the contrary avails, it will be prudent to assume that RMC

used in service will not exhibit as much strength as the 500 mm specimens tested here.

3) RMC composite strength appears to derive more benefit from an increase in mortar strength at low mortar strengths than it does at higher mortar strengths.

4) Local discontinuities between the phases caused by contaminated rock surfaces, bleed-water lenses and trapped air pockets appear to initiate general parting of the phases. Thereafter, failure appears to be governed by mechanisms which form between boulder inclusions. Rock fracture, as a result of high bearing stresses, is common where contiguous boulders interact and bear upon their adjacent neighbours. These bearing stresses appear to increase with increasing boulder size and stiffness. Elongated inclusions have an observed tendency to split, wedge or cleave the mortar matrix apart when their longitudinal axes lie near parallel to the principal compressive stress trajectories.

5) The uniaxial compressive strength of RMC appears to be affected by the orientation of elongated and/or flat inclusions with respect to the principal stress. As a result of this strength anisotropy, the predominant horizontal placement of boulders, which is inherent in most RMC structures built in recent times, is likely to significantly reduce their potential strength (particularly in arch structures). However, by simply altering the current practice of placing boulders, this strength anisotropy can be exploited to engineering advantage.

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CHAPTER 4

DEFORMATION[1] PROPERTIES OF RUBBLE MASONRY CONCRETE

4.1 BACKGROUND

Finite element models are increasingly regarded as ideal analytical tools for structural arch designs. They are extremely input-sensitive and depend on accurate knowledge of material stiffness for predicting structural response to loading and thermally induced strains, particularly in the case of large monolithic RMC dams. The current practice of guessing the stiffness of RMC, or at best assuming an equivalent concrete modulus, for want of a reliable estimate, undoubtedly compromises their outputs.

Although it may be argued that the Zimbabweans have successfully built many large wide-valley RMC arch dams empirically[(4.1)] and without knowledge of this material's elastic behaviour[(4.1,4.2)], there is cause for concern that the adoption of this practice elsewhere may result in unsafe structures. Their success may be attributable to a combination of favourable factors such as their almost exclusive use of granitic aggregates (which are not exceptionally stiff and which do not exhibit extreme coefficients of thermal expansion) combined with their temperate climate. Therefore, their precedent may not necessarily apply where engineers are

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The term "elastic modulus" has been deliberately avoided since the word "elastic" strictly implies fully recoverable deformation. Standard testing procedures[(4.20,4.21)] determine the elastic modulus of conventional concretes by subjecting test specimens to several load cycles before taking measurements to reduce the amount of non-recoverable deformation to a negligible level. However, as the strength and hysteresis of the RMC specimens, referred to here, were both unknown at the time of testing, their stress-strain relationships were observed from first ("virgin") loading. Thus, these measured strains include both recoverable and non-recoverable deformation components.

required to make use of other geologies in climates which experience greater temperature fluctuations, such as South Africa's. Shaw[4.2] has illustrated this by testing the response sensitivity of an idealized wide-valley arch dam to subtle manipulations of these parameters using a finite element model. His model predicts that maximum stresses (compressive and tensile) may be subject to an increase of as much as an order of magnitude, upon a realistic 10^0C temperature drop, as the material's elastic modulus is increased from 15 GPa to 40 GPa; assuming coefficients of thermal expansion typical of ordinary concretes.

In comparison to RMC, the elastic behaviours of conventional concrete and natural conglomerates are well understood. Alexander[4.3] has reviewed several methods of estimating the elastic modulus of ordinary concretes, based upon a relationship between elastic modulus and compressive strength[4.4-4.8] as well as micro-rheological two phase mathematical models[9-13] (shown in Figure 4.1). Whereas traditionally, the stiffness of concrete has been associated with its strength, recent research has shown that concrete strength *per se*, makes a relatively minor contribution to the composite's elastic modulus. The major contribution comes from the stiffness of the phases and their volume concentrations[4.14,4.15]. Thus, the mathematical two phase models would appear to simulate the true behaviour of ordinary concrete more realistically. However, these two phase concrete models do not account for the consequences of aggregate size and shape; factors which may be significant in RMC.

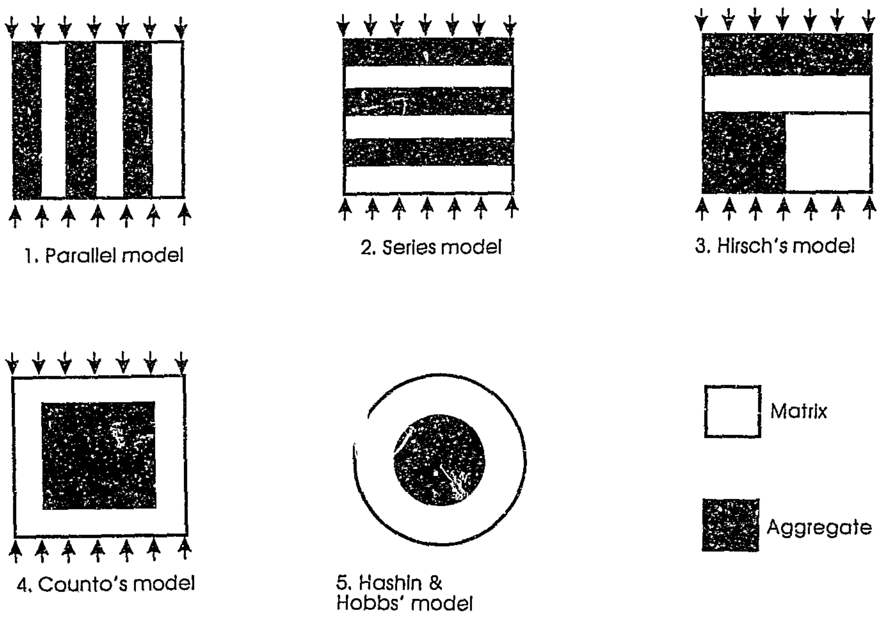


Fig 4.1 Existing theoretical two phase models for predicting the elastic modulus of concrete[4.3].

Beyond the ambit of concrete literature, Lindquist and Goodman[4.16], engaged in a study of rock mechanics, have shown by a series of triaxial tests on physical model melanges[2] that the modulus of deformation may be affected by the orientation of inclusions with respect to the axial loading direction (see Figure 4.2). Although their model melanges were intended to simulate the 'chaotic' fabric of confined rock, such as boulder conglomerate found in nature, their findings may be analogous to the similarly 'chaotic' man-made RMC melange. Unfortunately, their six inch (150 mm) diameter specimens were too small to permit exploration of the effect of inclusion size on stiffness. Moreover, in the literature consulted, the question of a relationship between stiffness and nominal aggregate particle size does not appear to have been addressed.

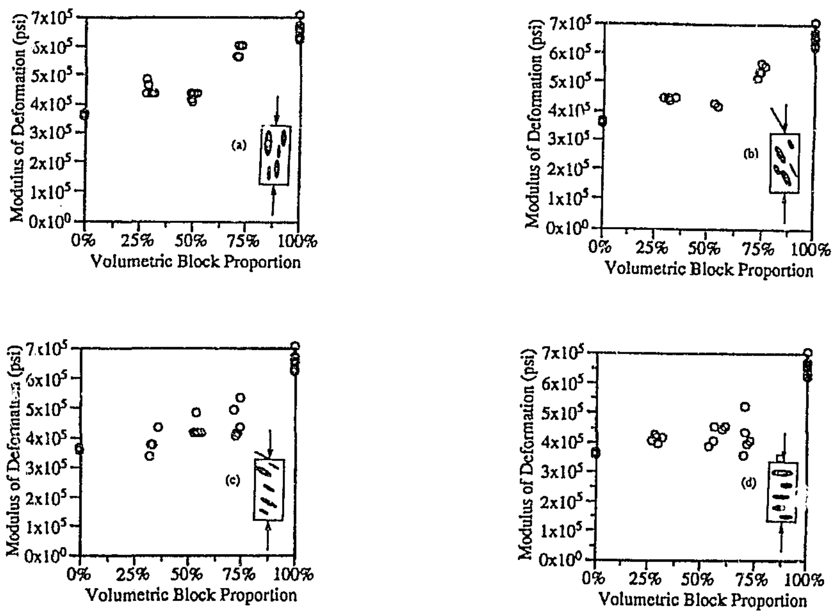


Fig 4.2 The effect of inclusion orientation (a) 0^0 (b) 30^0 (c) 60^0 (d) 90^0 with respect to axial load and volumetric block proportion (inclusion volume concentration) on the modulus of deformation of Lindquist and Goodman's[4.16] triaxially loaded melanges.

2

French word for a "mixture" of relatively large, competent blocks within a matrix of finer and weaker texture

Attempts[4.17,4.18,4.19] to measure the stiffness of large cubes of RMC, during tests where the primary objective was to determine compressive strengths and failure characteristics, have failed. These efforts included the use of a load-displacement drum recorder, mechanically connected to the mobile platen of an hydraulic press (as shown in Figure 4.3) and the use of pairs of displacement dial gauges. Both these methods produced questionable results for reasons listed elsewhere[4.29] (see Appendix 3).

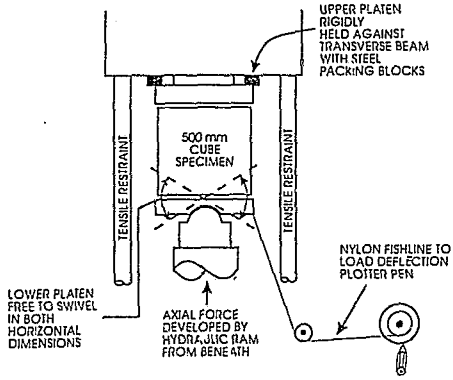


Fig 4.3 Line and drum displacement recording apparatus used in various preliminary attempts to measure stiffness.

4.2 EXPERIMENTAL

Most reported values of concrete elastic modulus have been derived from static tests[4.3], although dynamic methods, such as the ultrasonic pulse velocity (UPV) method, which exploit the relationship between medium stiffness and the transmission velocity of mechanical vibration, also exist. The static modulus is typically derived at a stress of one third[4.20] to 40%[4.21] of the specimen's strength with the load applied slowly over a period of minutes. On the other hand, the dynamic modulus is determined at fairly low stress with the load applied rapidly over a period of microseconds. Consequently, the dynamic method measures the initial tangent modulus and the static method measures the "secant" or "chord" modulus (see Figure 4.4). Both methods have their advantages and shortcomings depending on the application. The static method instills confidence for its simplicity of direct measurement under stress similar to the working stresses encountered by structures. However, because the static modulus is derived at a relatively high stress over a relatively long period, it usually includes an extraneous non-elastic (irrecoverable) component. In practice this hysteresis may be reduced, but seldom totally eliminated by subjecting the specimen to several load cycles before the strain which determines the modulus is recorded. Because the dynamic modulus is determined so quickly and at such low levels of stress, its non-elastic component is negligible. However, it remains unknown whether pulse velocity is independent of variations in specimen size and shape[4.22] and to what extent the presence of interfacial transition boundaries may cause interference - for example at discontinuities created by bleed-water and load induced cracks. Nevertheless, the relationship between statically and dynamically determined values of RMC stiffness warrants exploration since the latter may obviate the need for large unwieldy cube specimens in future.

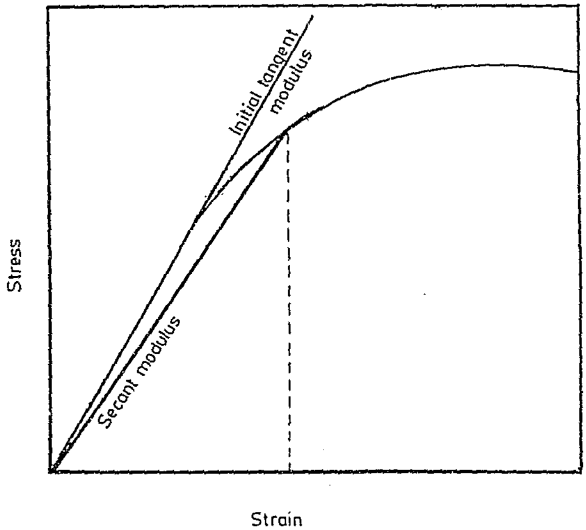


Fig 4.4 Two forms of modulus in brittle disordered materials which strain-soften upon fracture[4.3].

4.2.1 Test specimens

Existing standard test methods[4.20,4.21,4.23], used to determine the static modulus of elasticity in concrete, prohibit test specimens with an aspect ratio (length to diameter) of less than two. This ensures that the gauged length is not unduly affected by the confining influence of the platens. Conformance to this requirement would make the RMC specimens extremely difficult to handle as a minimum girth of 500 mm is needed to accommodate the large boulders. This dilemma was overcome by virtually eliminating friction at the platen/specimen interfaces and using 500 mm cubic test specimens. A considerable advantage in the choice of cubic specimens is that measurements of stiffness can be taken in more than one dimension, facilitating two sets of readings per specimen (both XX and ZZ dimensions). Three, 500 mm cubic specimens were manufactured according to a method[4.24] proposed specifically for RMC. To minimise the frictional platen constraint during testing, a double membrane of 250μm polyethylene sheeting, sandwiching a layer of petroleum jelly, was placed between the loaded cube faces and 6 mm hardboard packing above and below the specimens. A thin quadrant lip was bonded to the protruding edge of the lower hardboard packing as a precaution against possible lateral slippage of the entire specimen whilst under load (a potential consequence of the reduced friction).

Two of the cubes were cast, each containing different types of boulder inclusions and a third cube was cast with pure mortar as a control and with which to relate size effects during comparisons with nine, 100 mm cube and prism specimens. Dolomite from Olifantsfontein Quarry[4.25] and indurated siltstone from Leach and Brown Quarry[4.25] were chosen as aggregates, following work by Alexander and Davis[4.25], which showed these rock types to produce concretes with diametrically extreme values of elastic modulus over a wide range of concrete strengths (see Figure 4.5). Analogically, it is anticipated that the values of RMC stiffness obtained from this study, might similarly define the boundaries of a significant range of other rock types likely to be encountered. Such data may even be interpolated to estimate the composite stiffness where aggregates of intermediate stiffness are used. Moreover, the elongated shape of the siltstone fragments (a consequence of the fissility of this sedimentary rock) permits exploration of the effect of their orientation with respect to axial loading direction. A range of rock sizes up to about 20 kg (typical of the sizes used in RMC construction) was hand packed to maximise the volume concentration of stone. The bedding planes of the siltstone fragments were aligned parallel with one pair of mould faces to simulate the current practice of placing flat stones with their greatest dimension horizontal. A one part cement (including 30% fly ash) to four parts river-sand (by volume) mortar, with a 30 mm slump and 21.7 MPa 28 day, 100 mm cube strength was used for the matrix. The material properties are presented in Table 4.1.

Table 4.1 Specimen rock[4.27] and mortar properties and proportions. The elastic modulus of the mortar was measured statically in accordance with BS 1881: Part 121[4.20] using 200x100x100 mm prisms.

	Dolomite	Siltstone	Mortar
Elastic modulus (GPa)	109-118	24-27	18
Relative density	2.86	2.55 - 2.66	2.01 -2.16
Vol. fraction in cube (%)	43	23	100
Water absorption (%)	0.21	3.07	-
Uniaxial compressive strength (MPa)	212 - 396 (40 mm cylinder)	125 - 226 (40 mm cylinder)	21.7 (100 mm @ 28 days)

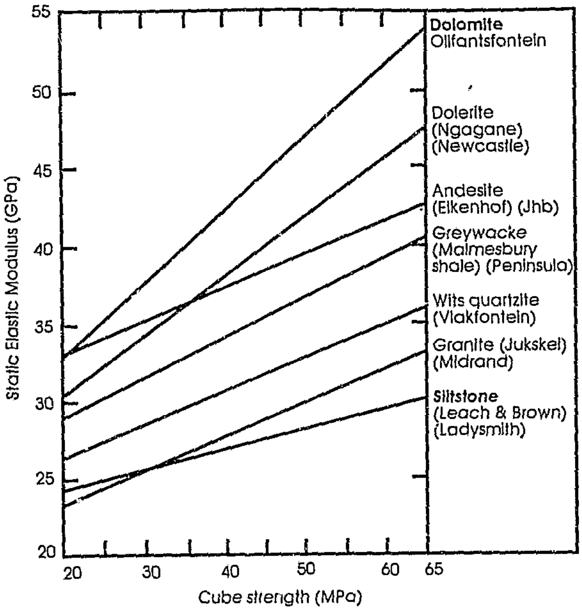


Fig 4.5 The relationship between the statically determined modulus of elasticity and cube strength of a range of common aggregates recorded by Alexander and Davis(4.25).

4.2.2 Apparatus

Most reported values of concrete elastic modulus have been obtained with static apparatus outlined in BS 1881: Part 121: 1983(4.20), ASTM method C469-87a(4.21) and RILEM CPC 8 (1975)(4.23). These standards make provision for the use of displacement compressometers as well as devices bonded onto the surfaces concrete specimens such as grids (which measure strain by moire' interferometry) and electronic strain gauges. The ASTM method restricts the minimum gauge length to not less than three times the maximum nominal aggregate size to reduce the probability of bias arising from locally dominant material concentrations. For this reason, a very long gauge length is desirable for RMC specimens (longer than affordable commercial gauges) and preferably almost as long as the length of the 500 mm specimens. The elimination of the bonded gauge option prompted the development of a compressometer (shown in Figure 4.6), with two square yokes monitoring a gauge length of 80% of the cube, based upon the ASTM design and an independent micrometer for measuring dilation between targets fixed centrally to diametrically opposite vertical faces midway between the loaded surfaces. Several practical difficulties in reading the micrometer manifested during first testing. The restricted space between the platens made access to the targets difficult, the size of the micrometer necessitated an extra pair of hands to support its distal end and its aluminium frame lacked sufficient stiffness to repeatedly measure a constant distance. Consequently, the micrometer was abandoned and the compressometer was modified by the addition of an extensometer illustrated in Figure 4.7.

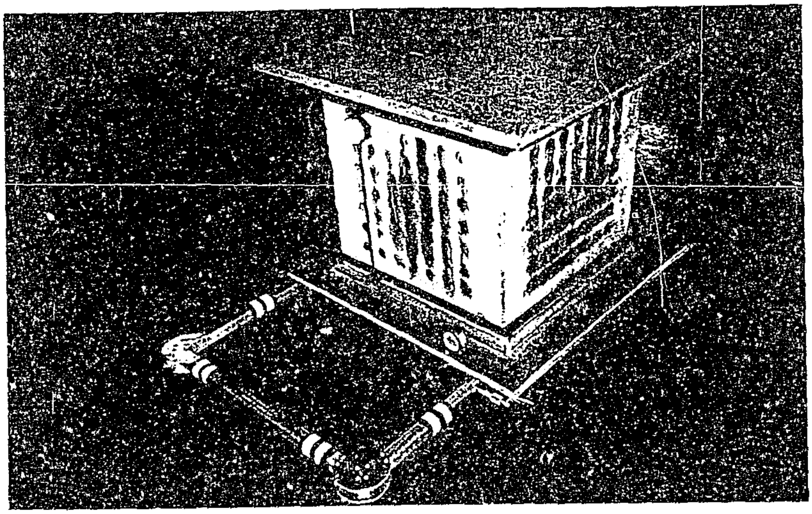


Fig 4.6 Prototype compressometer attached to a 500 mm RMC cube specimen and micrometer (foreground) built to measure moduli of deformation and dilation respectively.

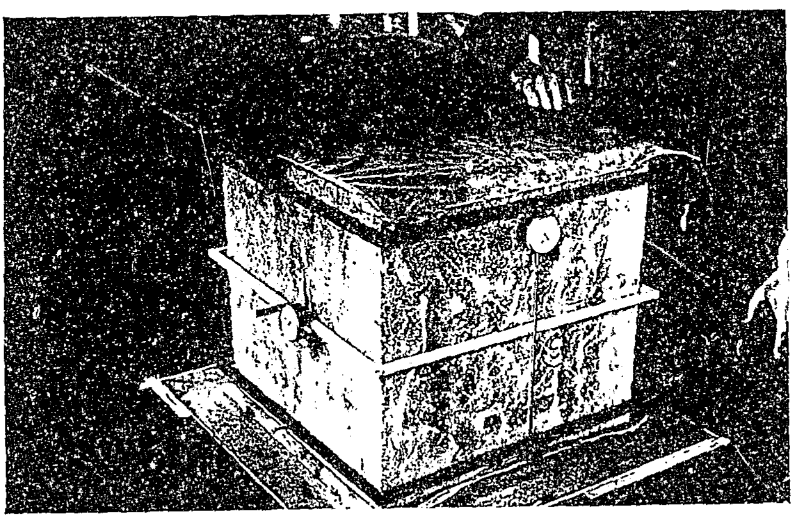


Fig 4.7 Improved integrated compressometer/extensometer to measure both axial strain and lateral strain. The gauges measure twice the actual strain. The double polyethylene slip membrane can be seen between the upper face and the packing.

An ultrasonic pulse velocity recorder (shown in Figure 4.8) was used to record the dynamic modulus of each cubic specimen. Because of the material's anisotropy, 49 readings were taken over a regular square grid with the aid of two templates, one of which is shown in Figure 4.8 (in each dimension XX,YY & ZZ), to obtain an average.

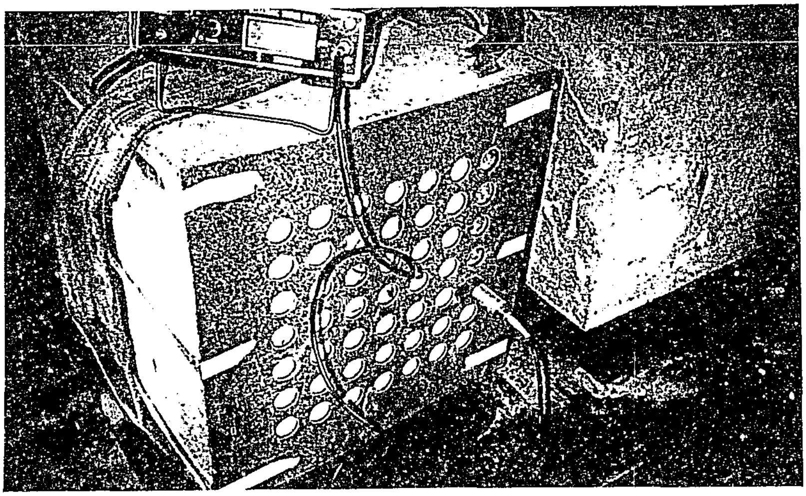


Fig 4.8 Ultrasonic pulse velocity recording apparatus used to determine the dynamic tangent modulus of RMC specimens prior to static testing.

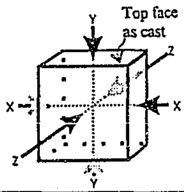
4.2.3 Testing

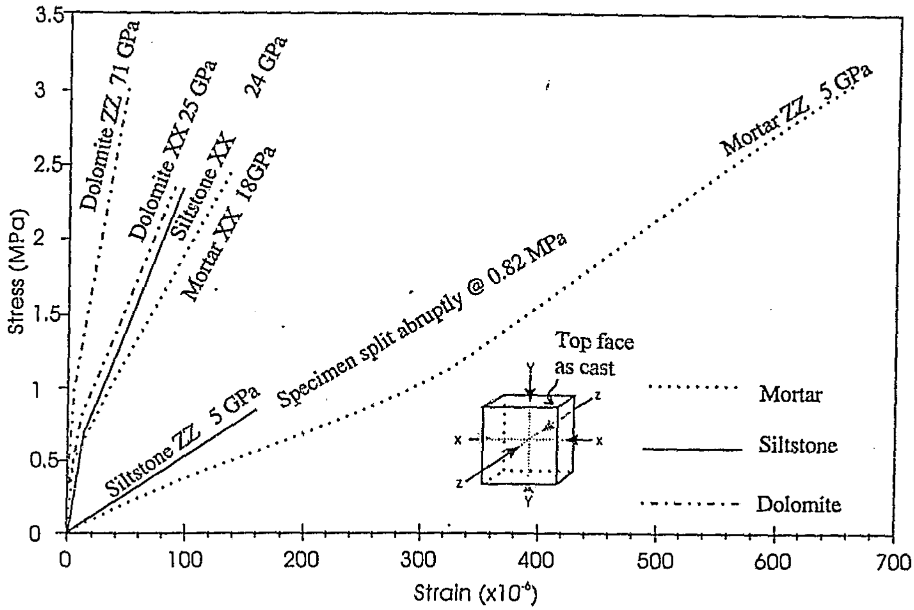
The ultrasonic testing was conducted prior to the static testing to preclude the possibility of interference arising from material discontinuities caused as a consequence of load-induced cracking. The results are summarised in Table 4.2. Thereafter, "static" load was applied using the 1000 short ton (907 metric tonne) press at the CSIR Mine Hoisting Laboratory at Cottesloe Johannesburg. Load was applied first to the designated XX axis (the anticipated strongest direction in the case of the siltstone; perpendicular to the longitudial orientation of the elongated specimens)[3]. The specimens were then rotated through 90^0 and reloaded orthogonally to their first loading, along their ZZ axes. The results are summarised in Figures 4.9A and 4.9B. Static strains were recorded from virgin (first) loading because there was no means of predicting each specimen's ultimate compressive strength and hysteresis.

3

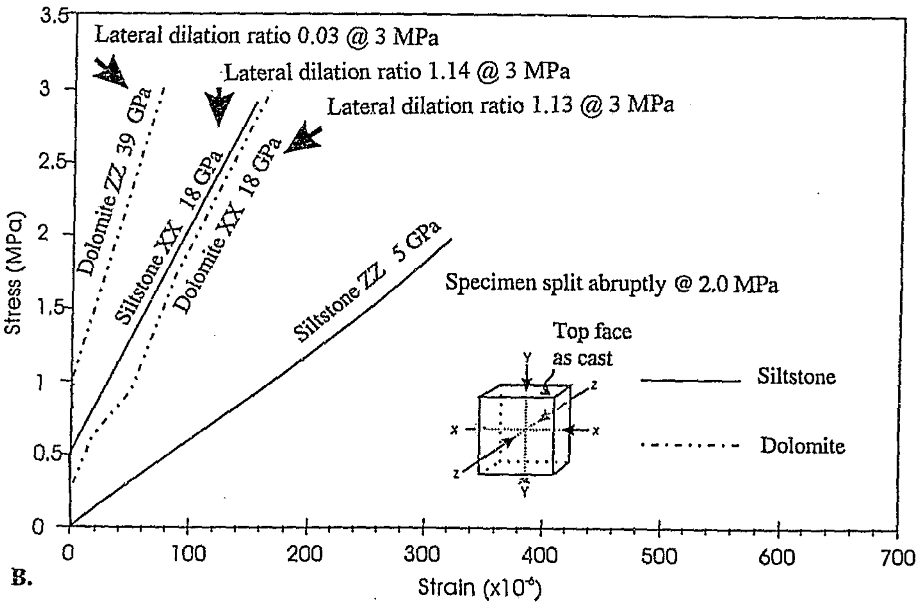
The siltstone was first loaded along its strongest axis to increase the probability of it remaining intact for the second static test.

Table 4.2 Initial tangent moduli measured dynamically along different axes with the ultrasonic pulse velocity apparatus shown in Figure 4.8.

	Mean dynamic elastic modulus (GPa) $\bar{x}$	Standard deviation from the mean (GPa) σ	Coefficient of variation (std. dev. from mean as a percentage of the mean) $\sigma/\bar{x}$	Range of moduli (Max - Min) (GPa)
Dolomitic cube				
XX	65.3	9.6	14.7%	38.1
YY	55.5	6.6	11.8%	25.2
Siltstone cube				
XX	40.4	3.6	8.8%	15.1
YY	36.4	3.1	8.4%	11.3
ZZ	29.0	1.8	6.1%	8.8
Mortar cube				
XX	24.6	0.5	2.2%	2.3
YY	24.4	0.6	2.3%	2.6



A.



B.

Fig 4.9 Graphical comparison of the stress strain-relationship of the test specimens upon testing with the prototype device shown in Figure 4.6 (A) and upon subsequent retesting with the improved device shown in Figure 4.7 (B). The moduli shown are secant moduli calculated at the highest possible stress. The lateral dilation ratio recorded as the siltstone specimen was XX loaded was measured parallel to (in line with) the siltstone bedding planes.

4.2.4 Discussion on physical testing

The vast differences in stress-strain behaviour between alternate axes of individual specimens are indicative that this is an aelotropic material which is sensitive to shape and orientation of its rock inclusions. In fact, comparing values in Figure 4.9, the stiffness of RMC appears to be influenced more by boulder shape and its orientation than by rock stiffness. A significant reason for this phenomenon may be attributable to the convergence of composite elastic values (containing a variety of rock) as concrete strength decreases towards the stress levels encountered in RMC - evidenced in Figure 4.5.

The statically measured deformation moduli (secant moduli) were, without exception, lower than those determined dynamically (initial tangent moduli). This is to be anticipated in brittle disordered materials such as concrete which strain-soften upon fracture (see Figure 4.4). The consistency with which the dynamic apparatus is capable of predicting the composite's initial tangent modulus (as evidenced by the coefficients of variation in Table 4.2) appears to be related to homogeneity and perhaps to the ratio of inclusion to matrix stiffness. The pure mortar specimen, which was the most homogeneous in the group, showed the best consistency, followed by the specimen containing siltstone. The superior consistency of ultrasonic pulse data from the RMC specimen containing siltstone might be ascribed to the similarity in stiffness between the siltstone and its mortar matrix. As the stiffness of the rock approaches that of the matrix, the transmission velocity of mechanical vibration becomes less affected by the disordered inclusions (ie. the ultrasonic pulse is less able to distinguish between the two phases). Thus, it would appear that dynamic methods of elastic measurement may be better suited to RMC containing softer rather than harder inclusions.

An examination of Figures 4.9A and 4.9B reveals a marked contrast in specimen stiffness between XX loading and subsequent ZZ reloading in every case. The "virgin" XX loading curve of the pure mortar specimen in Figure 4.9A shows slight strain softening up to the final stress of 2.5 MPa, at which loading was terminated when fine vertical cracks became visible. Its subsequent ZZ loading curve steepens under increasing stress; suggesting that the material stiffened after the cracks (now perpendicular to the load) closed. The much lower subsequent modulus (upon ZZ loading) is probably the result of significant strain within the cracks (now perpendicular to the ZZ reloading axis) during crack closure. In contrast, the absence of visible cracks upon "virgin" XX loading in the specimen containing siltstone and the linearity of its ZZ loading curve call for an alternative explanation for the low stiffness recorded along its ZZ axis. Theoretically, an increase in modulus ought to accompany a rotation of elongated inclusions (with respect to the principal stress) from perpendicular to parallel. Simple models such as the one proposed by Hirsch[4.10] for concrete and the finite element model illustrated in Figure 4.12 show that when the stiff bands are parallel to the principal stress they attract more of the axial stress. The result is a stiffer composite. Moreover, Lindquist and Goodman's[4.16] physical triaxial tests (see Figure 4.2) further support this theory. The departure of the siltstone specimen from this theory might be due to the mechanical action of the stones fracturing the composite by a wedging and cleaving action at low levels of stress. Indeed, this specimen split abruptly at only 0.82 MPa when it was compressed along its ZZ axis (parallel to the stones' longest axes). It was then carefully prized apart for examination. Fracture appeared to have initiated at the stone-mortar interface, parallel to the principal stress. The specimen was then bonded together with an epoxy before being reloaded. Its subsequent behaviour (see Figure 4.9 B) was similar. Again, when its ZZ axis was stressed, it split parallel to the previous fracture (now repaired) at a slightly higher stress of 2 MPa, by which time its rate of dilation, as measured perpendicular to the siltstone bedding planes by the mechanical extensometer (shown in Figure 4.7), exceeded its axial deflection by such an order that its visual recording proved impossible.

The behaviour of the specimen containing dolomite is perplexing. Its chunky shape might have been expected to yield a composite with similar properties in both the XX and ZZ axes. However, the stiffness measured in the ZZ axis proved more than double that measured in the XX axis in both tests. Furthermore, the dilations measured perpendicular to those same axes differed by nearly [illegible] times. Since the stiffness measured during ZZ loading exceeded the XX "virgin" stiffness by a large margin, this discrepancy cannot be attributed to strain-weakening and/or fracture closure. Examination of the origin of the ZZ gradient in Figures 4.9A and 4.9B shows an abnormally high initial modulus (measured statically); perhaps as a result of a very favourable distribution of rock in that axis but maybe as a result of a discontinuity near to the gauge. Unfortunately, the absence of dynamically recorded data about its ZZ axis precludes a comparison with a dynamically predicted modulus in this axis.

Without exception, measured dilation was greatest in the plane orthogonal to the axis of least stiffness. Mechanisms which may be responsible for this dilation are illustrated in Figure 4.10. These mechanisms appear capable of inducing lateral strains which exceed their principal counterparts. In Figure 4.9 B, the ratio of lateral (dilational) strain to principal strain has been called the lateral dilation ratio for want of a better term. This is analogous to Poisson's ratio but is not limited to the material's elastic phase.

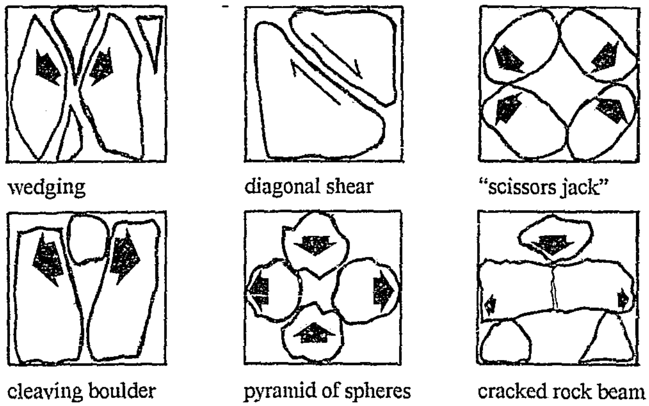


Fig 4.10 Mechanisms which may result in high values of dilation.

4.3 IDEALISED THEORETICAL MODELLING

4.3.1 The effects of spherical inclusion size and suspension within the matrix on stiffness

Two series of six idealised RMC melange models, containing uniform cubically packed spherical inclusions, were analysed using a two dimensional finite element model ("Prokon" Groenkloof SA & London UK Second Beta Plane Stress/Strain Analysis) to explore the relationship between inclusion size, composite stiffness and maximum internal stresses. In the first series, the inclusions make intimate contact with their neighbours and the platen surfaces, whereas the inclusions of the second series are separated from one another as well as the platen surfaces by a layer of mortar. In each series, the inclusion volume fraction remains constant throughout each of the six cases and is 0.524 and 0.382 respectively. A 10 GPa mortar matrix stiffness and a 100 GPa inclusion stiffness (a tenfold composite phase stiffness ratio) were simulated; bordering the highest variance anticipated in practice. A Poisson's ratio of 0.1 is assumed and stiffness is recorded at a stress of 3 MPa. The model assumes perfect bond to the inclusions and the platens. Furthermore, uniform strain of the load surfaces is assured by a pair of "infinitely stiff" platens. The results of the theoretical analysis are presented in Tables 4.3a and 4.3b and typical compressive stress distributions are presented in Figure 4.11 Note that shear stresses are not shown in Figure 4.11.

Table 4.3a Relationship between contiguous idealised spherical inclusion size, composite stiffness and maximum internal stresses derived theoretically using a finite element model. The values apply to Series 1 where the inclusions are contiguous.

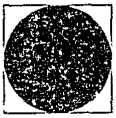
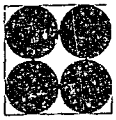
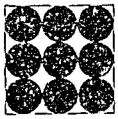
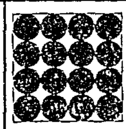
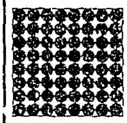
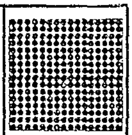
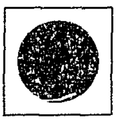
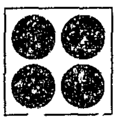
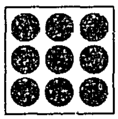
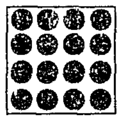
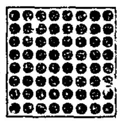
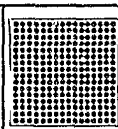
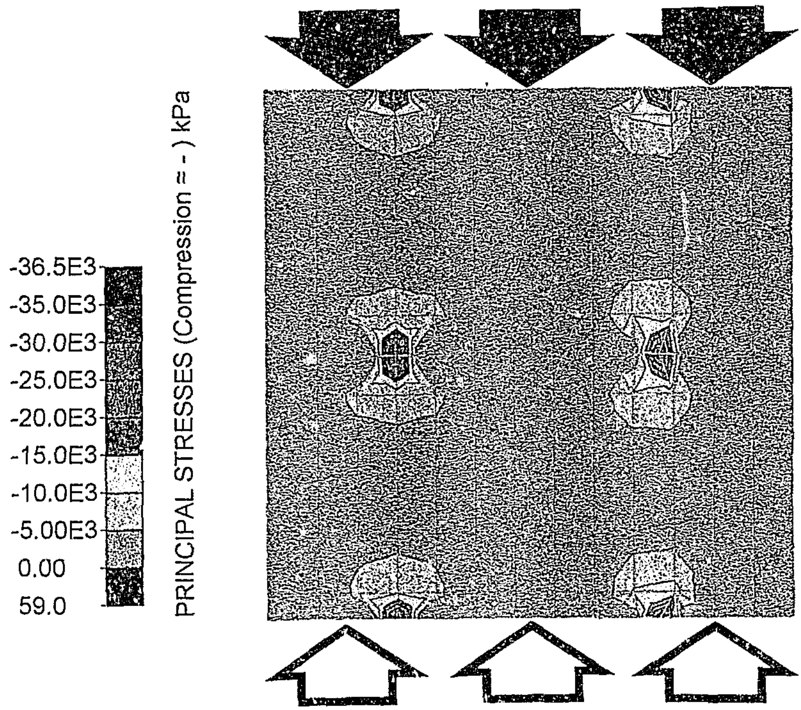
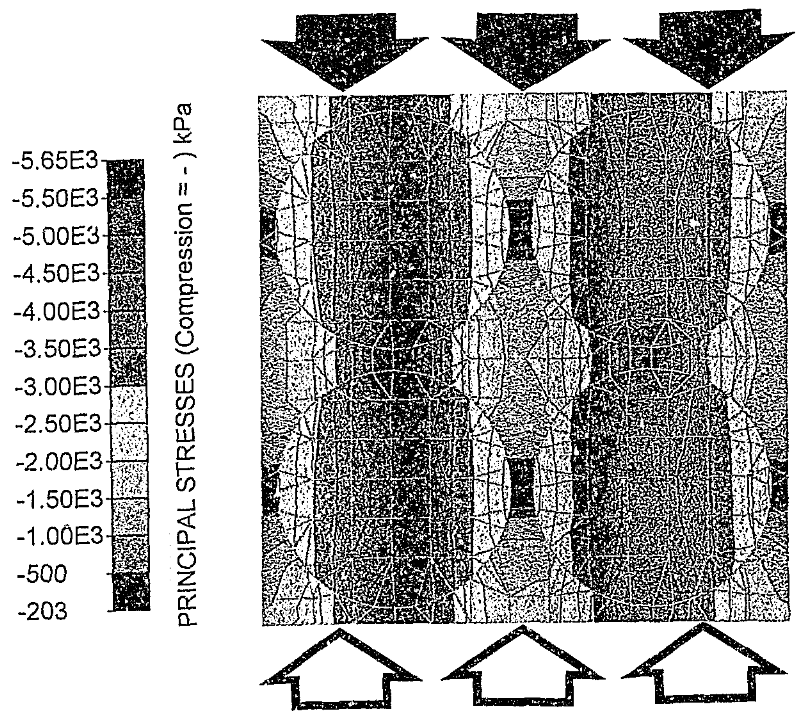
SERIES 1 Inclusions in contiguous contact Vol. fraction stone = 0.524						
Inclusion diameter mm	1000	500	333	250	125	63
Particle volume ℓ	524	65	19	8	1	0.1
No of particles/m^3	1	8	27	64	512	4096
Specific surface m^2/m^3	3.14	6.28	9.42	12.57	25.13	51.07
Composite stiffness GPa	27	29	30	33	40	43
Max comp stress (MPa)	66	38	32	27	18	7
Max tens stress (MPa)	19	10	7	5	4	3

Table 4.3b Relationship between idealised suspended (within the matrix) spherical inclusion size, composite stiffness and maximum internal stresses derived theoretically using a finite element model. The values apply to Series 2 where the inclusions are separated by a bed of mortar.

SERIES 2 Inclusions separated by a bed of mortar. Vol. fraction stone = 0.382						
Inclusion diameter mm	900	450	300	225	113	56
Particle volume (ℓ)	382	48	14	6	0.7	0.09
No of particles/m^3	1	8	27	64	512	4096
Specific surface m^2/m^3	2.54	5.09	7.63	10.18	20.36	40.72
Composite stiffness GPa	32	32	32	32	32	32
Max comp stress (MPa)	[illegible]	(<6)	(<6)	(<6)	(<6)	(<6)
Max tens stress (MPa)	(<1)	(<1)	(<1)	(<1)	(<1)	(<1)



A.



B.

Fig 4.11 Typical compressive stress distributions; in the case of spherical inclusions touching one another (**A.**) in the case of spherical particles floating in a matrix of mortar (**B.**) E3 = 10^3

4.3.2 The effects of particle orientation, with respect to principal stress, on stiffness

The material properties, volume fractions and geometry of the siltstone specimen were modelled using the same finite element theory and assumptions described previously. The model was "test-loaded" both parallel and perpendicular to the longitudinal axes of the elongated inclusions. The simulation was repeated with inclusions of stiffness equal to the dolomite used in the physical tests but in all other respects identical. A schematic of the model is presented in Figure 4.12 and the results are presented in Table 4.4.

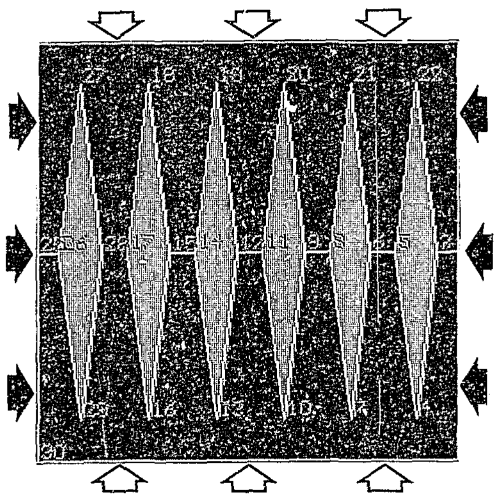


Fig 4.12 Idealised theoretical two dimensional model simulating the siltstone specimen's deformation behaviour assuming perfect retention of interfacial bond. Solid arrows indicate how load was applied perpendicular to the inclusions' longitudinal axes. Hollow arrows indicate how load was applied parallel to the inclusions' longitudinal axes

Table 4.4 Theoretically simulated composite stiffness perpendicular and parallel to the axes of elongated inclusions of differing stiffness.

Inclusion stiffness (GPa)	Composite stiffness perpendicular to inclusions' longitudinal axes (GPa)	Composite stiffness parallel to inclusions' longitudinal axes (GPa)
25 (siltstone)	14	15
121 (dolomite)	17	25

4.3.3 Discussion on theoretical modelling

Examination of the theoretical output presented in Table 4.3 reveals a marked contrast in behavioural response between the composite containing idealised spherical inclusions in intimate contact with one another and the composite containing inclusions floating in a soft mortar matrix. While the stiffness of the former appears to increase as the inclusion size decreases, the stiffness of the latter appears unaffected. Thus, it would appear that a bed of mortar effectively neutralises the size effects of perfectly bonded inclusions. Furthermore, maximum internal stresses around points of contact appear to decrease as the number of inter-particle contacts per cross sectional area, orthogonal to the principal stress axis increases. Theoretically, the contact area between touching spheres or spheres and plane surfaces is infinitesimally small, regardless of their size. Thus, substantial stresses under even small inter-particle forces evolve. An increase in the number of inclusion contacts per unit area in the plane orthogonal to the principal stress axis results in load sharing (among a greater number of stiff columns of contiguous spheres) and the consequent lowering of contact stresses. This is analogous to the model shown in Figure 4.13 where the 'columnar' supports (the columns of contiguous spheres which attract stress) are represented by springs in parallel. Since the contact area between spheres is assumed to be infinitesimally small, regardless of the sphere dimensions, the stiffness of all springs may be assumed to be equal. Therefore, the greater the number of springs per unit of stressed area, the lower the stress in each spring. Since strain is proportional to stress, the greater the number of springs per unit area, the less they will deflect. Hence, the composite experiences an overall stiffening.

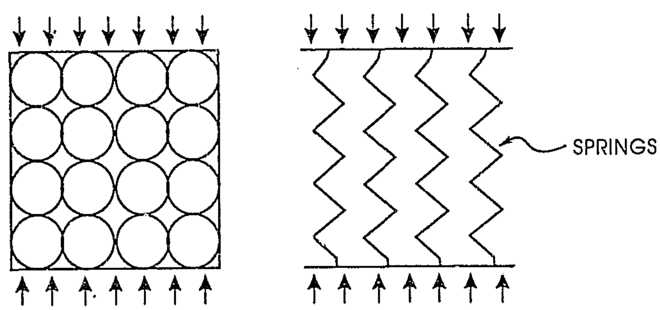


Fig 4.13 Analogous spring model where the columns of spheres are represented as equivalent springs.

Limitations of the theoretical finite element model

In reality, the structure of RMC bears little resemblance to the idealised theoretical form modelled above. The real material departs from this theoretical model in at least the following respects:-

1) The shape of real boulders is never spherical, they are never uniform in size and they are never perfectly packed.

2) The interfacial bond is unlikely to remain intact under high stress.

3) Despite the customary deliberate attempts to minimise the mortar matrix content (which results in the stones making intimate contact), the proportion of critical contacts capable of increasing composite stiffness may be less when inclusions are not regular and true.

4) RMC typically adopts a twisted orthorhombic packing arrangement which is theoretically optimal[4.23]. Although the inefficient cubical packing arrangement of the model reproduces the volume fraction of aggregate reportedly achieved in practice, this is probably a coincidence brought about by the absence of sharp protrusions which would otherwise prohibit regular close contact between inclusions in reality. A more complex three dimensional model capable of simulating the twisted orthorhombic packing arrangement would be a logical progression for profitable future research.

5) The bilateral platen constraint offered to the loaded surfaces of real test specimens is not infinite.

6) The model is a two dimensional replica of a three dimensional problem.

Nevertheless, the model illustrates the principle whereby load is attracted to the stiffest parts of the composite and how the enhanced distribution of this load reduces the composite strain. It also illustrates the advantage of a mortar bed in eliminating high contact stresses where very large inclusions are used and/or the wisdom in limiting the maximum size of boulders.

4.4 CONCLUSIONS

1) The selection of two rock-types representing the extremes of the range of stiffness likely to be encountered and the radical manufacture of one of the cubic test specimens yielded a wide range of statically measured deformation moduli (between 5 GPa and at least 39 GPa) and lateral dilation ratios (between 0.03 and more than one).

2) In addition to the exponents currently recognised to govern the stiffness of conventional concrete (namely the stiffness of the individual ingredients, their volume fractions and maturity), boulder shape and orientation appear to have a significant effect on RMC stiffness and dilation, probably more so than rock stiffness. The unfavourable orientation of slender or flat inclusions (with their longest axes parallel to the principal stress) promotes mechanisms which may destroy the interfacial bond between phases and fracture the material at low stresses. This appears to cause premature softening and high levels of dilation.

3) Dynamically determined initial tangent moduli were consistently greater than the statically measured secant moduli as expected.

4) Dynamic methods of determining initial tangent moduli appear better suited to RMC containing softer, as opposed to harder, rock types.

5) A theoretical finite element model has illustrated how the presence of a thin layer of soft mortar, separating very large stones, may be effective in reducing maximum stress levels within the composite.

6) RMC stiffness appears sensitive to the number of inter-particle contacts disposed to carry load within the principally stressed area. Thus, many small contiguously placed boulders will produce a stiffer composite than a few large isolated plums.

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CHAPTER 5

THERMAL STRAIN BEHAVIOUR OF RUBBLE MASONRY CONCRETE

5.1 INTRODUCTION

Thermal stresses develop when materials are prevented from expanding or contracting freely in response to temperature changes. On a structural scale, large monoliths, such as dams constrained by valleys, may develop significant thermal stresses. On a 'micro-scale', composites experience internal thermal stresses, even though they may have no external restraints. This is because their dissimilar (in terms of stiffness and rates of thermal expansion) material phases are forced to strain compatibly.

Because RMC structures, such as dams, are usually built monolithically, without joints to facilitate differential movements, it is imperative that designers take cognisance of thermal stresses which may add significantly to the load-induced stresses. In the absence of reliable RMC thermal expansion data, designers may be tempted to disregard thermal stresses and refer to precedent alone or to substitute improvised data which is applicable to conventional concrete. The implications of this uncertainty have been clearly demonstrated by Shaw[5.1]. Assuming deformation moduli and coefficients of linear thermal expansion of ordinary concretes, Shaw computed the magnitude of thermally induced stresses in an idealised wide valley monolithic arch dam (typical of many that have been built of RMC to date), subject to a temperature drop within the structure of only 10^0C below placement temperature. His computation estimates thermally induced stresses to be many times greater than the live-load induced stresses. In some instances thermally induced critical tensions were well in excess of the tensile capacity of masonry. Notwithstanding, it is acknowledged[5.1,5.2], even by Shaw, that RMC structures are almost entirely devoid of visible cracks. Shaw attributes this anomaly to the fortunate coincidence of a relatively temperate climate in Zimbabwe - where most RMC structures have been built - combined with the fact that most of them contain granitic aggregates which he claims are "*ideal for producing a composite which manifests low thermal stresses since* *granite has low thermal expansivity and a lowish elastic modulus*". Although these factors may be significant in limiting thermal stresses, there would appe[illegible]e some other mitigating factor/s as well.

1) Firstly, several RMC dams have recently been built in more extreme climates, in other parts of southern Africa including Lesotho[5.3], Vrede in the Free State[5.4] and Bushbuckridge in Mpumalanga[5.5]. One of these structures[5.5] was even cast over a period when ambient conditions were well in excess of the placement temperature of 22^{0}C, which Shaw assumes for the purposes of his analysis. In this instance, ambient temperatures were so high that saturated boulders are reported to have become completely surface dry during the short wheelbarrow trip between the wash site and the work face, only a short distance away[5.6].

2) Secondly, only one of these structures[5.5] contained granite while the others contained much stiffer basalt[5.3] and dolerite[5.4].

Nevertheless, there is an apparent absence of visible cracking and associated leakage in all RMC structures built to date. This chapter presents an hypothesis to account for the apparent absence of visible post-hydration cracking in large monolithic RMC structures built to date. It also makes several recommendations to minimise the risk of thermal cracking in more ambitious structures and structures exposed to severe environments.

5.2 THERMAL MOVEMENT IN CONVENTIONAL CONCRETE - A REVIEW

The response of a particulate composite, such as concrete, to temperature fluctuations is governed by a complex evolution of local stresses between the phases (as a result of their contrast in stiffness and differential rates of thermal expansion) and creep behaviour. Aggregate inclusions in concrete tend to be stiff and thermally stable, whereas the cementitious paste matrix tends to be "softer", and more thermally expansive. Comparing the coefficients of linear thermal expansion; aggregates typically vary from about 4 to 11.5 x $10^{-6}/^0C$ [5.7,5.9], mortars vary from 8 to 13 x $10^{-6}/^0C$[5.8] and the hardened cementitious pastes vary from about 11 to 20 x $10^{-6}/^0C$ [5.8,5.9]. The elastic moduli of aggregates typically vary from 20 to 120 GPa[5.7], and hardened cement pastes typically vary between 5 and 25 GPa [5.10].

Numerous investigators[5.7,5.8,5.11,5.12,5.13] have reported that thermal volume changes of concrete are strongly influenced by the coefficients of thermal expansion of the phases. It has subsequently become accepted that the coefficient of linear thermal expansion of concrete is proportional to that of its aggregate(5.11,5.12). The volume fraction of aggregate has also been shown to influence thermal movement as shown in Figure 5.1(5.7,5.13). In general, the coefficient of expansion of rock has been shown to increase with increasing silica content and consequently aggregates containing a high quartz content tend to exhibit the highest coefficients while calcareous aggregates have been found to exhibit the lowest coefficients(5.7). Nevertheless, wide variations of coefficients of expansion do exist within single rock types(5.13).

No theoretical model, capable of predicting the thermal strain response of a particulate composite (based on a thorough knowledge of the properties of the individual phases) appears to exist. Furthermore, the literature consulted appears not to have considered the effect of aggregate size, shape and orientation on the composite's coefficient of expansion.

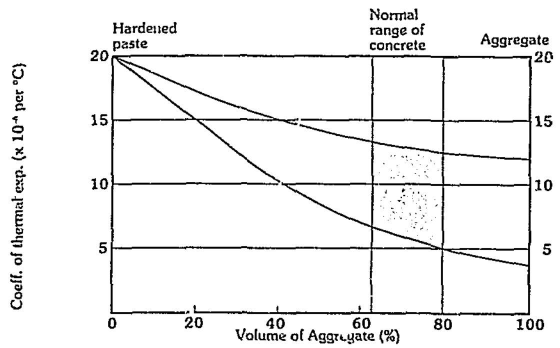


Fig 5.1 Thermal expansion of concrete containing varying volume fractions of aggregates with different coefficients of thermal expansion(5.13).

5.3 AN HYPOTHESIS TO PROVIDE AN EXPLANATION FOR THE THERMAL STRAIN BEHAVIOUR OF RMC

The following hypothesis is based on the premise that RMC is distinguishable from conventional concrete in at least three respects:-

1) Typically, the boulder size is about one order of magnitude larger (in linear dimensions) than stone aggregate used in conventional concrete.

2) Boulders are forced into the mortar so that they bear contiguously upon one another.

3) River-sand, which typically contains a high proportion of quartz[5.14], is used for making the mortar. As a result of the high thermal expansion coefficient of its quartz content, this mortar exhibits a relatively high thermal expansion coefficient.

5.3.1 Statement of the hypothesis

On account of its large boulder inclusions, RMC exhibits lower thermal strain than equivalent conventional concrete. Provided these inclusions are contiguous and constitute the stiffer and thermally less responsive phase, the composite will exhibit a reduced thermal strain response below its placement temperature.

5.3.2 The influence of large particles on thermal strain behaviour

Assuming the two phases remain intimately and rigidly connected by a perfect unyielding bond, then the magnitude of internal thermally evolved stress is independent of the length of the matrix/aggregate interface since the units of length cancel. On this premise, inclusion size has no bearing upon the magnitude of stress developed between the phases, nor can it affect the thermal expansion of the composite.

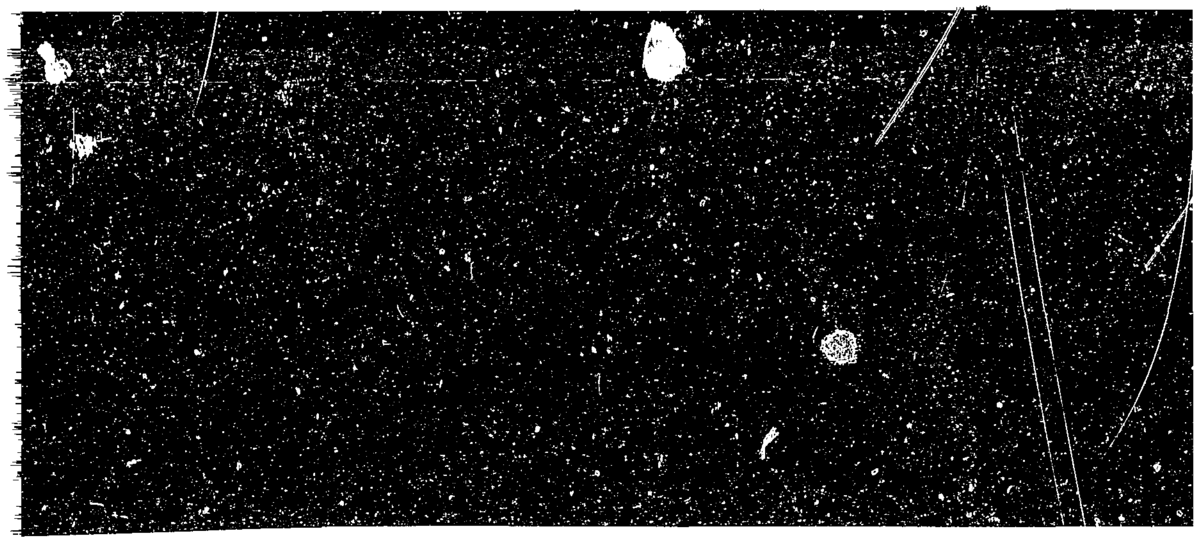
However, in practice the two phases may not remain perfectly bonded. A physical investigation of the thermal response of epoxy mortars, carried out by the author together with Morris[5.15,5.16], showed a significant reduction in composite expansion coefficient (almost 20%) as the nominal particle size of stiff inclusions was increased. The explanation proposed was that creep in the epoxy matrix surrounding of the inclusions, acted as a mechanism for relieving internal stresses and was less inhibited by small particles than by large particles. Similarly, creep in a hardened cement paste/mortar matrix may be more effective in relieving internal stresses around small inclusions than around large boulders.

Concrete technologists refer to the presence of a third phase - the Interfacial Transition Zone (ITZ) - which is thought to exist as a result of a layer of water which accumulates on the surfaces of aggregate particles, preventing cement particles from packing efficiently. This ITZ has been described as a weak, porous layer (about 50 μm thick[5.17]) of relatively high water/cement ratio, whose mechanical properties differ from those in the bulk paste [5.17,5.18]. Alexander[5.19] has noted that the ITZ is relatively compressible and that it prevents "proper interaction between paste and the (usually) stiff aggregates, thus lowering the stiffness of concrete". This seems to be corroborated by the observation that stone has a greater effect on concrete stiffness than its sand derivative[5.7]. The significance of the ITZ, in the context of this argument, is that its thickness remains relatively constant regardless of the size of the aggregate. Very small inclusions are unlikely to exercise much restraint on a more active matrix if the ITZ surrounding them is able to yield sufficiently to accommodate the small relative movement between the two phases which occurs as a consequence of temperature change. As the inclusions become bigger, the ITZ surrounding them (which remains only 50 μm thick) has reduced capacity to accommodate the relatively larger movement of the larger particles and the two phases are forced to strain compatibly, thereby evolving internal stresses. Large inclusions are therefore more effective than small inclusions in suppressing thermal strains in RMC.

5.3.3 Thermal strain behaviour as a consequence of contiguous particle action

Above the placement temperature, thermal strain of the matrix will predominate since there is little to prevent the inclusions from being pushed apart. However, below the placement temperature, the high thermal strain of the matrix is checked by the relatively stiff and unyielding inclusions which are effectively immobilised by their contiguous bearing upon their adjacent neighbours (illustrated in Figure 5.2). Consequently, the matrix experiences a net tensile stress and in extreme circumstance (ie. a significant temperature drop) this restraint may cause a cohesion failure within the matrix or an adhesion failure at the interface. This is illustrated by a simple test shown in Figure 5.3. Glass marbles were cast contiguously in a matrix of transparent polyester resin at a temperature of 20^0C. When heated above the casting temperature to 50^0C, the predominant expansion of the matrix pushed the stiff inclusions apart, thereby governing the composite's expansion and a linear expansion coefficient of about $60 \times 10^{-5}/^0$C was observed. However, when cooled below the casting temperature to -10^0C, the tensile stress within the matrix exceeded its cohesion and bond failures occurred adjacent to the 'equators' of the inclusions where the matrix cross sectional area was least. Thus, it may be deduced that the contraction of the matrix was restrained by the relatively stiff and unyielding inclusions bearing contiguously upon their neighbours.

RMC may similarly exhibit differing thermal expansion above and below its placement temperature although the contrast will not be as pronounced as the case above since mortar is more thermally stable than polyester. However, provided the inclusions are stiffer and more thermally stable than the matrix, as is usually the case in RMC, the thermal response below the placement temperature will be lower than above this temperature. This has not only been



observed in sand filled epoxy resins[5.15,5.16] but its corollary was noted in tests[5.20] on fibre-reinforced polymer composites. Above the casting temperature, the thermally stable and relatively stiff fibres constrained the more active but softer matrix. Below the casting temperature, the more active thermal behaviour of the matrix predominated as the slender fibres were able to exercise little restraint in compression.

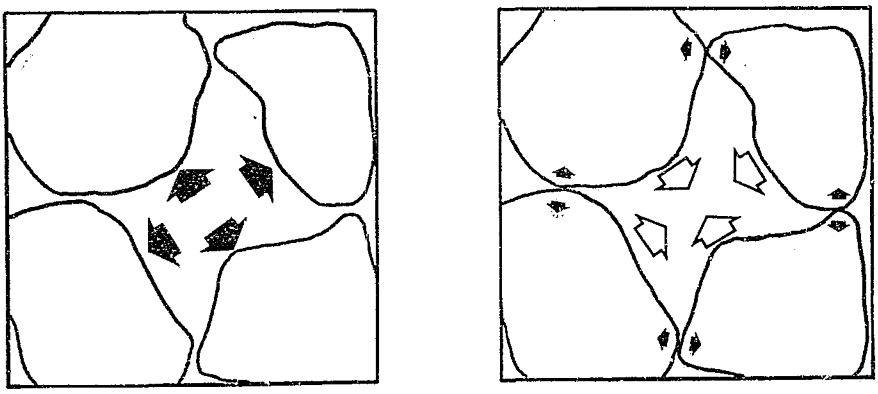


Fig 5.2 Model proposing a different rate of thermal expansion above (left) and below (right) the casting temperature. Above the casting temperature, adjacent boulders (shaded) are free to be pushed apart by the mortar matrix but below casting temperature the boulders bear contiguously against their neighbours, inhibiting the composite's contraction.

Fig 5.3 Glass marbles cast in a matrix of transparent polyester resin demonstrate the dual response of a particulate composite with contiguous inclusions about its casting temperature.

5.4 TESTING THIS HYPOTHESIS

Past efforts(5.21) to explore the thermal strain of concrete (in the field and in the laboratory) have used mechanical 'Demec' gauges to measure the relative displacement between pairs of targets bonded to the surfaces of prismoidal specimens.

5.4.1 The choice between field measurements and laboratory measurements

There are several problems which may make field measurements of thermal strains in RMC structures impractical.

Firstly, the daily temperature fluctuation (amplitude) within the body of a RMC structure is unlikely to be sufficient to cause significant strain. In fact, the greatest temperature differential will probably occur over a six month period with a maximum temperature experienced after noon shortly after mid-summer and a minimum temperature experienced shortly before dawn just after mid-winter. This long delay precludes the use of apparatus whose outputs may vary with time and changing moisture levels (for example, electronic resistance strain gauges and amplifiers). Furthermore, during these peak temperatures, the structure's outer surface temperature is unlikely to be the same as the core.

Secondly, even the longest Demec gauge lengths are too short to include a representative section of RMC. Therefore, readings are likely to be heavily biased by individual boulder inclusions and/or large volumes of mortar.

Thirdly, it is sometimes difficult to ascertain whether material measured in the field is unrestrained and able to expand freely.

After considering these difficulties, a decision was taken to explore the thermal strain behaviour of RMC in the laboratory.

5.4.2 Choice of testing apparatus

Demec gauges offer the advantage that the gauge is made of invar and that it can remain at a relatively fixed temperature since it need only be connected to the specimen briefly to take measurements. This obviates the need to thermally calibrate the device with respect to some setting piece whose length can be guaranteed to remain constant. However, the Demec gauge was not adopted for exploring RMC properties because of concern that the surface strain of a RMC specimen may not be truly representative of the composite strain. Ideally, a temperature calibrated strain measuring device, capable of being heated with the specimen while measuring small thermal strains above and below the placement temperature is needed to quantify coefficients of linear thermal expansion of a range of rock types. Unfortunately, efforts to calibrate this apparatus were not successful. The high cost of acquiring a bar of calibrated invar precluded its use and the latent action within the dial gauge precluded the use of another material, at constant temperature, as a removable setting/distance piece.

Fig 5.4 Apparatus for exploring the thermal strain behaviour of RMC cube specimens.

Consequently, attempts at calibration were abandoned and the apparatus shown in Figure 5.4 was built to explore only relative thermal strains. I[illegible] of an annealed thick steel

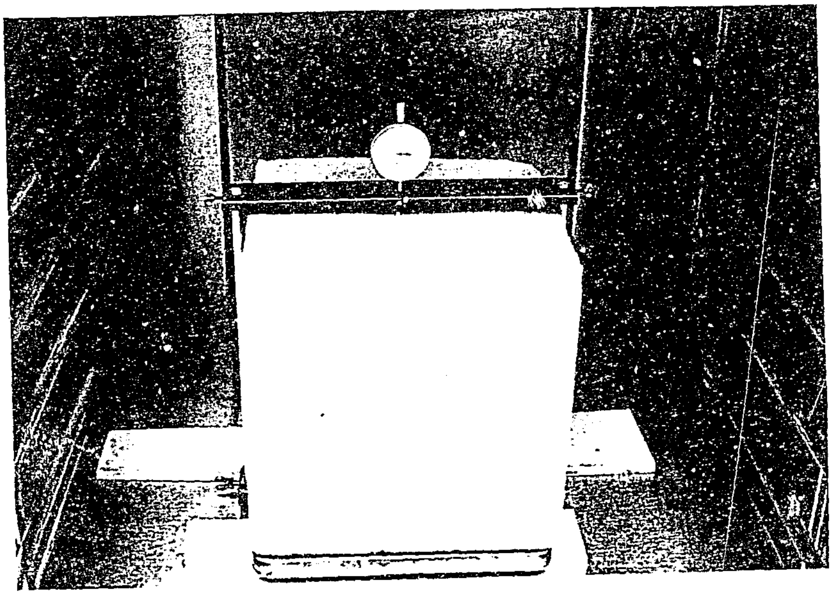


Fig 5.5 Relative thermal strain measuring apparatus with a 300 mm RMC cubic specimen shown in the oven prior to testing. The polyethylene bag which was wrapped around the specimen to limit moisture changes during heating has been omitted for clarity.

Letcher[5.22] used this apparatus to explore the relative thermal strains of RMC cubes containing boulders exhibiting extreme coefficients of expansion; namely dolerites and quartzites The materials were preheated and cast at a temperature of about 40 °C to facilitate approximately equal recording ranges above (40 °C to 90 °C) and below (40 °C to -10 °C) the placement temperature. Specimens were first tested dry (as a precaution against the risk of damage due to pore water freezing) and then tested saturated (to isolate the extraneous effects of dessication shrinkage). Although there remains uncertainty about the setting temperature after placement and the consistency of the reference temperature (40 °C), Letcher's study may have qualitative merit. The "extensions" plotted above (at 90 °C) and below (at -10 °C) the reference temperature appear distinctly non-linear - indicative of a lower "thermal contraction coefficient", in all cases, irrespective of whether the reference temperature is assumed to be 25 °C (the lowest possible temperature - ambient temperature), 40 °C (the most likely saturated (to isolate the extraneous effects of dessication shrinkage). Although there remains uncertainty about the setting temperature after placement and the consistency of the reference temperature (40 ^{0}C), Letcher's study may have some qualitative merit. The "extensions" plotted above (at 90 ^{0}C) and below (at -10 ^{0}C) the reference temperature appear distinctly non-linear - indicative of a lower "thermal contraction coefficient", in all cases, irrespective of whether the reference temperature is assumed to be 25 ^{0}C (the lowest possible temperature - ambient temperature), 40 ^{0}C (the most likely temperature) or 50 ^{0}C (a temperature 10 ^{0}C higher that the initial temperature of the ingredients - possible only if the evolved heat of hydration exceeded the heat loss to the environment by a significant margin).

5.5 DISCUSSION

The hypothesis of a lower coefficient of linear thermal expansion below the placement temperature provides a plausible explanation for the apparent absence of post-hydration cracks within large monolithic RMC dams built in wide valleys. A reduced thermal response beneath the placement temperature would mitigate the tendency for the structure to contract upon a temperature drop. Instead, thermally induced tensile stresses are absorbed internally, on a 'micro-scale', in the form of tension within the mortar matrix between the inclusions. Thus, the evolution of composite tensile stress, which RMC is least able to withstand, is reduced. Above the placement temperature, RMC is better able to accommodate larger strains since it is stronger in compression. Moreover, arch structures may be able to accommodate some of this expansion by deflecting slightly upwards (upstream in the case of dams) - a reaction checked by load, albeit self-weight..

Letcher's[5.22] preliminary investigation shows qualitatively that RMC appears to exhibit a reduction in thermal expansion coefficient below the casting temperature. He has also identified obstacles to measuring the thermal expansion of RMC. Further research is needed to quantify absolute values of thermal expansion in larger, more representative specimens and to provide designers with conclusive data as to the range of values likely to be encountered in practice. In subsequent tests, great attention needs to be paid to the establishment of the composite's internal temperature at the time of setting.

5.6 PRACTICAL RECOMMENDATIONS

1) Because the risk of distress, due to thermal strain, is greatest in the event of a temperature drop below placement temperature, efforts to reduce the placement temperature of materials should be encouraged. Boulders exposed to direct sunlight can become very hot and increase the rate of hydration thereby promoting faster exothermic heat generation (their temperature at the time of setting may be higher than at the time of placement). Figure 5.6 shows a simple test to determine the maximum temperature of three different rock types exposed in Johannesburg during a peak summer period where ambient temperature was about 30 ^{0}C. All the specimens tested attained maximum temperatures of between 55 ^{0}C and 60 ^{0}C after midday. Restricting building operations to the winter months and pre-wetting or placing hot boulders in the shade, prior to bonding them into the structure, would help to reduce placement temperatures.

2) Based on the above hypothesis, it may be tempting to speculate that larger monolithic structures might be safely constructed using large, low coefficient, stiff boulders without concern of tensile cracking as a consequence of a significant temperature drop. However, internal fractures may result if a severe temperature drop is encountered. Such failure was noted by Pearson[5.23] where a low thermal expansion coefficient dolomitic marble was used as concrete aggregate in a northern American region. Failure, in the form of an interfacial bond separation of the type shown in Figure 5.1, was described. In many parts of southern Africa, dolerite, which is relatively stiff and which exhibits a low thermal expansion coefficient, exists abundantly. Unless it is freshly quarried, it tends to exhibit a chemically weathered surface[5.24] which is not conducive to good interfacial bonding. These characteristics of dolerite are liable to promote disintegration of the composite in the event of a severe temperature drop. Thus, if dolerite is specified, it is imperative that boulders should have sound surfaces (preferably freshly broken) to promote good adhesion and that their maximum size should be limited.

3) In the absence of a reliable coefficient of thermal expansion for RMC, it will be prudent to adopt values of equivalent conventional concrete. Assuming the hypothesis is true, the adoption of equivalent concrete data would yield conservative designs.

Fig 5.6 An experiment to determine the maximum temperature attained in rocks exposed in the sun in Johannesburg. Holes were drilled into which thermometers were inserted with a conductive coupling agent. From left to right, Bakubung foyaite from the Pilansberg National Park, Olifantsfontein Quarry dolomite and Karoo ecca. All rocks attained similar maximum temperatures of between 55 ^{0}C and 60 ^{0}C.

5.7 CONCLUSION

It has been hypothesized that, in addition to factors known to govern the thermal expansion coefficient of conventional concrete, inclusion size and particle contiguity may have an effect upon the thermal response of RMC. Where boulder inclusions are thermally less responsive and stiffer than the matrix phase, their contiguous interaction may be expected to reduce the composite's coefficient at temperatures below placement by precluding closer packing of boulder inclusions. This may contribute to the apparent absence of post-hydration thermally induced cracks in wide valley monolithic RMC dams. The use of rocks such as dolerites, which are very stiff and exhibit particularly low thermal coefficients and poor bonding characteristics may result in severe internal distress and should be used with caution. Precautions to limit thermally induced masonry tensile stresses, by limiting the placement temperature, are recommended. Finally, until reliable quantified coefficients of thermal contraction for RMC avail, the use of equivalent data derived from conventional concrete tests and/or predicted values for concrete appears to be the safest means of estimating a structure's thermal response.

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CHAPTER 6

HUMAN LABOUR CONSIDERATIONS

6.1 INTRODUCTION

While most engineers appreciate the importance of achieving acceptable quality standards and structural competence in their RMC structures, little attention appears to be paid to the problem of "fitting the task to the man". Many engineers and contractors, who are extremely fastidious about the fuel efficiency and maintenance of their mechanical plant, are apparently unconscious of the nourishment, health and effectiveness of human beings engaged in their physical workforces. This oversight is not unique to our present day. Indeed, Robert Owen(6.1), a successful 19th century Scottish mill owner, expressed it succinctly, in an essay addressed to superintendents of factories:-

> *Many of you have long experienced in your manufacturing operations the advantages of substantial, well-contrived and well-executed machinery. If, then, due care as to the state of your inanimate machines can produce such beneficial results, what may not be expected if you devote equal attention to your vital machines which are far more wonderfully constructed?*

Before making recommendations and drawing conclusions in the chapters that follow, this chapter will consider factors which enable human beings to labour effectively. Recent statistics are reviewed to identify and characterise the targeted unemployed population. Human labourers are compared with man-made machines to establish the relative energy and economic efficiencies of man and machine. Lastly, guidelines to make more effective use of human energy for constructing RMC structures are presented.

6.2 CHARACTERISATION OF THE TARGETED POPULATION GROUP

6.2.1 The background to modern day unemployment and poverty

Until about 1750, the world carried out its daily work in much the same way as it had done for more than 2000 years before, and a contemporary of Pericles would probably have had little difficulty in making himself at home in the England of George III. The hand-tools of the weaver, carpenter and smith resembled those shown on ancient Egyptian monuments. Before 1750, there were no machines, such as those which now perform much of man's work, to mass-produce goods which formerly only the wealthy could afford. Since then, mankind has seen technical changes more drastic than any others recorded in history. The Industrial Revolution arose out of the evolution of machinery for the spinning and weaving of cloth. It exponentially increased the production of almost every conceivable commodity. In many cases, the poor have become poorer as these machines have increasingly undermined the value of their labour - particularly unskilled labour, on all continents and in both the Third and Developed Worlds. Indeed, Rifken[6.2] estimates that by the year 2010, only two percent of the North American workforce will consist of "blue collar" workers, compared with 33 percent during the 1960's. This diminishing capacity for manual labour has a detrimental effect on employment among the poorest countries. As a consequence of their lack of marketable skills and education, their workforces are deprived of alternative, more intellectually demanding employment opportunities.

6.2.2 The current magnitude of unemployment and poverty

Of the world's estimated 2.5 billion labour force, 120 million (almost 5%) are formally unemployed and this figure excludes unaccounted millions more who have given up all hope of finding work[6.3]. Globally, three billion people currently live on less than US$2 per day[6.4]. Africa, as ranked by the World Bank[6.5], is presently the most destitute continent on the globe with 14 of the 36 poorest countries in the world, including the three poorest.

South Africa is currently ranked the 16th poorest country in the world[6.5] with eight million of her people living on less than US$1 per day[6.5] and estimated unemployment figures[1*] of 32,6%[6.6] and 40%[6.3,6.7]. An additional problem is that most unemployed South Africans are currently unemployable beyond the status of unskilled manual labourers. Of those unemployed, about 65% have had no previous occupation and 87% are not trained or skilled for any specific type

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Recently, the definition of unemployment was changed to exclude jobless people who have not actively sought work in the four weeks prior to being interviewed. According to the Central Statistical Services[6.78], in terms of the new definition, only 23% of South Africans were unemployed in 1998. This new definition does not therefore take into account the true extent of joblessness in our economy.

of work[6.6]. Furthermore, over 50% of her black working population is illiterate[6.8]. Her high population growth rate, coupled with her industry's diminishing labour-absorption capacity[6.9] (from 73,6% in 1970 to 12,5% in 1990)[6.7] only serve to exacerbate the problem as illustrated by the schematic in Figure 6.1. Economic growth will have to increase by more than 100% just to accommodate new additions to the labour-force (currently estimated at 2,8% per annum)[6.7]. Therefore, so long as her population growth remains unchecked and economic growth does not increase dramatically, the enhancement of her unskilled labour-absorption capacity is of paramount importance in ensuring South Africa's prosperity.

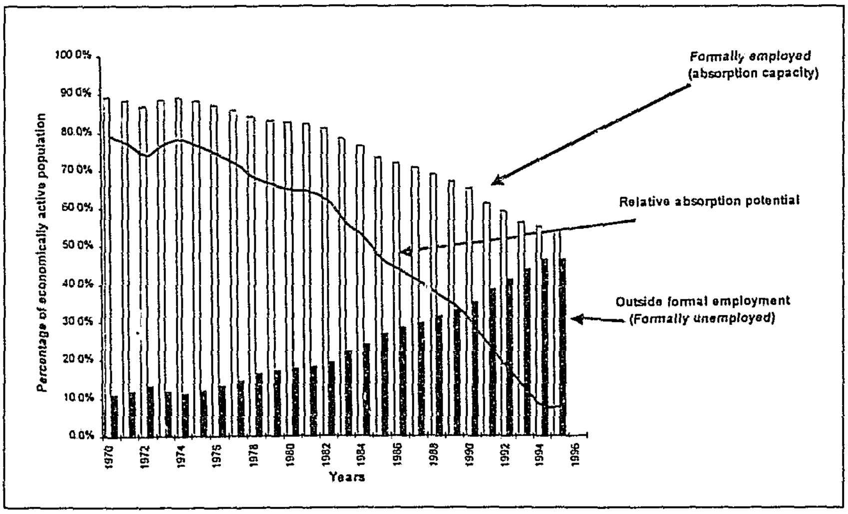


Fig 6.1 The formal employment absorption capacity of the South African economy (Source: DBSA, 1997)

Unfortunately, poverty appears to be self-perpetuating. Of the world's forecast population increase (about a billion persons in the next decade), about ninety percent of this increase will occur in the low-income, developing countries where resources are already severely strained[6.3,6.10]. Such rapid population growth can only exacerbate the problems of unemployment, starvation, disease, homelessness, lack of infrastructure and illiteracy which already cripple these countries.

6.2.3 The distribution and standing of the targeted population group

Standish [6.11] has proposed that labour-intensive construction initiatives should aim to alleviate poverty by targeting the poorest of the poor. He proposes that this is achieved by offering a wage so low (R7 per day in 1994) as to dissuade all but the most needy destitute. Figure 6.2 shows the distribution of the poorest population groups in South Africa. Overwhelmingly, the rural areas are most affected; particularly the former Transkei, Bophuthatswana, Venda and Ciskei. Moreover, poverty appears to be more prevalent in the eastern parts of the country. Illiteracy and a lack of skills within the southern African black community appear as common denominators and foundation stones of poverty throughout most of these areas[6.11]. Therefore, the sale of their unskilled manual labour appears to be one logical escape from their cycle of poverty. However, many of the most destitute groups are not all well disposed to selling even their labour. The Target Focus Group of the National Public Works Program[6.11] in South Africa has identified single women with dependents, the elderly without pensions and the partially disabled (who fall outside the ambit of welfare programmes) as being among the most needy recipients of employment. Therefore, there may be a strong argument in support of organising activities and developing hand tools to make physically demanding tasks less taxing.

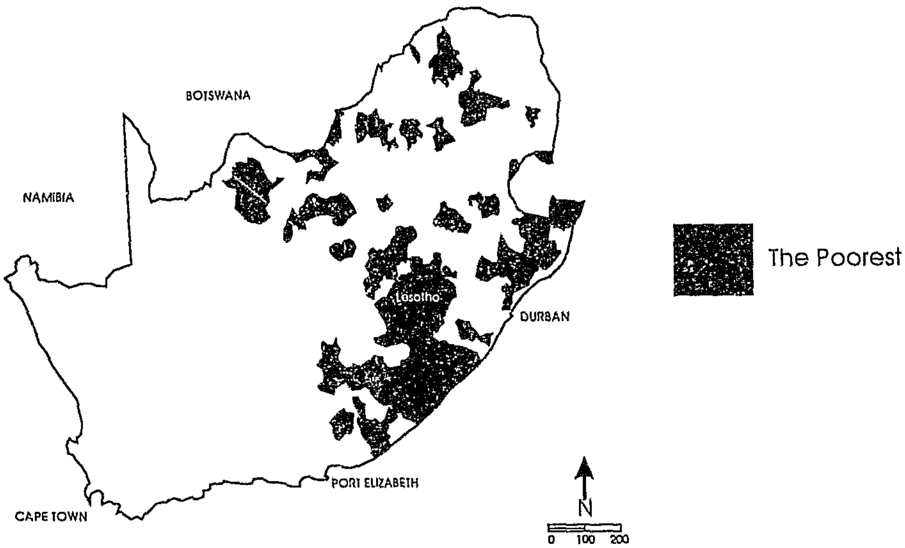


Fig 6.2 Geographical location of the poorest (lowest per capita income) of all population groups in South Africa. Source 1991 Census[6.11].

6.2.4 Health and nutritional status of southern African labourers

The people of sub-Saharan Africa reportedly suffer one of the world's highest per capita burden of debilitating disease[6.12] (see Table 6.1). There is consensus that southern Africa's health status is continually declining for numerous reasons, the most dominant of which would appear to arise out of her vicious cycle of poverty. The growing number of the population below the poverty line in sub-Saharan Africa is expected to have a substantial impact on health in the future[6.13]. Shortages of land, food and employment as a consequence of population pressure and droughts, throughout the subcontinent, have generated major population movements to urban centres[6.14,6.15]. Concentrations of large populations in small geographical areas have resulted in slum areas. Health care facilities with sparse resources focus on death control as their main priority rather than the promotion of health or birth-control. Consequently, there is a growing proportion of survivors exposed to the risk of chronic, degenerative diseases[6.16]. This is exacerbated by the fact that children frequently suffer the consequences of malnutrition and lack of immunisation[6.15]. Slums become heavily polluted and drinking water is often contaminated by excreta. As a consequence, there are frequent epidemics of communicable diseases like cholera and dysentery[6.15,6.17]. Furthermore, this migrant urban population is characterised by a predominance of males since African men frequently find employment far from their families. These males are more likely to have multiple sexual partners[6.18]. Moreover, it has been suggested[6.18] that this society has adopted some of the most unconscionable habits and morals of both Western and Third World civilisations. Old tribal customs and mores are increasingly giving way to the more pervasive culture and values of the so-called "First World" yet there is continued exploitation of women and the young by older males[6.18]. While sexual freedoms in the West have been encouraged by the availability of barrier methods, easy access to medical facilities, a high level of education and economic independence, these factors are absent in many parts of Africa[6.18]. There are also reports of increasing chronic diseases of lifestyle among black Africans such as poor diet, substance abuse, smoking and alcohol consumption[6.19,6.20]. Intakes of energy, fat and protein are rising while carbohydrate and fibre moieties are diminishing[6.19,6.20]. Lesser dependence on plant foods has reduced intake of vitamins[6.19,6.20]. As a result, prevalence of dental caries, obesity, diabetes, hypertension and stroke have risen to exceed levels in western populations[6.19,6.20,6.21].

Research towards improving conditions in the Third World is not economically lucrative. Honey[6.12] argues that because diseases like malaria affect mostly poor or Third World countries, drug companies are unwilling to invest money in developing new drugs to combat them. According to the World Health Organisation[6.12], only one thousandth of the budget spent on health research worldwide in 1990-1992 was spent on anti-malaria research, a disease noted by Markus[6.23] as one of the three most important unconquered human diseases (apart from AIDS). Furthermore, the cost of many currently available drugs to combat complicated diseases like AIDS is prohibitive to health-care services in developing countries[6.18].

Certain diseases like malaria and tuberculosis are highly efficient in developing resistance to drugs[6.12,6.24]. Intermittent treatment of victims, albeit due to a shortage in supply or a lack of continuity in administering drugs, has been shown to have resulted in the evolution of extremely militant strains of diseases[6.12,6.24]; aptly termed "drug-resistant" which are usually incurable. In fact, there is an argument[6.12] that some communities, in isolated areas not well supplied with anti-malaria drugs, are better off as a result since the malaria parasite has not had an opportunity to develop drug immunity while the human population has developed its own 'semi-immunity'.

Many diseases are opportunistic and work synergistically in tandem with other diseases to the detriment of a victim. Tuberculosis is an example of such a disease. Its bacteria lie (mostly dormant) in 60% of all South Africans[6.25] and when a victim's defences are compromised by HIV infection, malnutrition or some other ailment, the symptoms of chronic TB manifest[6.26]. Thus, a large proportion of the AIDS and TB death statistics are probably conjoint.

Relationship between impaired health and human capacity to perform physical work

That well nourished, healthier individuals work harder may seem intuitively appealing. However, there is a dearth of sound quantitative medical evidence on the prejudicial effects of these debilitating diseases and nutritional deficiencies upon human physical working capacity, since little is known of the levels of physical performance loss associated with measurable burdens of infections and definable states of inadequate nutrition[6.27]. It is easy to misinterpret what appear to be simple correlations between production and physical impairment since numerous problems arise in establishing the causal link. In practice, it is difficult to isolate control variables in an environment where extraneous phenomena abound and, until recently, portable apparatus for measuring the energy consumption (currently one of the best indicators of physical work output) of workers was not widely available. Furthermore, the extent to which these research findings can be generalised to larger populations is often jeopardised by sample attrition[6.28].

However, despite this inadequate medical knowledge, there are economic sources which claim that this consequent reduction in physical working capacity may be significant. For example, the South African Chamber of Commerce has stated[6.12] that malaria "is having a serious effect on KwaZulu Natal and Mpumalanga, and seriously retarding the progress of industry, trade and agriculture in these provinces and, through them, the country". In Uganda, the economic impact of AIDS has been observed in changing agricultural patterns. Fallow land is expanding and income farming has decreased while subsistence farming is on the increase. Furthermore, the number of harvests and live-stock has also decreased[6.18]. Slawski[6.29] reports that "managers to the north of South Africa, for example, are over-staffing and training three new employees for one position to allow for AIDS related absenteeism and death".

Table 6.1 Brief statistics of the high debilitating disease burden in Africa.

Disease		Recent statistics in Africa
AIDS	1)	Central Africa was the birthplace of HIV[6.18] and of the estimated 30 million people infected worldwide[6.30,6.31], about 63% of them live in sub-Saharan Africa[6.31].
	2)	About 90% of HIV infections occur in developing countries[6.31].
	3)	HIV/AIDS accounts for a third of all deaths from infectious diseases in sub-Saharan Africa[6.31].
	4)	Prevalence rates of up to 30% are reported from some countries[6.32].
	5)	80% of the worlds infected children are domicilc in Africa[6.18].
	6)	HIV prevalence among South African adults is currently estimated to be about 10.5%[6.18] (about three million persons infected[6.31]) and rising rapidly. By 2005 Doyle* predicts this will rise to 18-27% [6.18].
	7)	South Africa's epidemic is increasing unchecked with an increasing 1000 "new" infections acquired daily[6.18].
	8)	At this time there is no local evidence of any reduction in HIV spread[6.18].
	9)	In southern Africa, HIV infection is highest among the working-age population[6.34].
Parasitic infections	1)	Sub-Saharan Africa is characterised by the most powerful malaria vector system in the world - accounting for more than 80% of the 120 million clinical cases estimated in the world in one year[6.35].
	2)	Every year 70% of sub-Saharan Africans fall ill with malaria and at least 640 000 of them die[6.12].
	3)	Malaria accounts for 9% of sub-Saharan Africa's disease burden[6.12].
	4)	Malaria incidence has exceeded population growth in recent years[6.12].
	5)	Schistosomiasis (bilharziasis) is estimated to be present in 75 million Africans[6.28].
Tuber-culosis	1)	South Africa has one of the worst TB epidemics in the world with 60% of her population infected[6.25].
	2)	TB killed 10 000 South African's in 1996:- more than any other infectious disease - and made 160 000 people sick[6.36].
	3)	More than 2000 South African's fell ill with multi-drug resistant TB in 1996, for which there is little chance of survival[6.25].
	4)	Dormant TB bacteria are likely to flare up as an individuals immune system is compromised in any way. Therefore, AIDS victims are more likely to succumb to death by TB[6.26].
Hepatitis B	1)	This virus is 100 times more infectious than AIDS (yet it is spread in the same way) and is carried by 10% of South Africa's black population[6.37].
	2)	There is presently no cure and up to half the chronic carriers of this virus will die of cirrhosis and/or liver cancer[6.37].
	3)	Mozambique has the highest rate of liver cancer in the world[6.37].
	4)	The disease is more prevalent among males[6.37].

* There are numerous conflicting statistics on the prevalence of AIDS in South Africa. One survey[6.33] (March 1996) estimated the doubling time to be 5 to 12 months by which time it predicted that four million South Africans would be infected. However, the Doyle prediction (from 1991) is probably more accurate since recent reviews of Doyle's work suggest that this prediction remains valid[6.18].

6.3 A COMPARISON BETWEEN HUMAN LABOURERS AND MAN-MADE MACHINES

A machine has been defined[6.38] as "*any arrangement for the purpose of taking in some definite form of energy, modifying it and delivering it in a form more suitable for the desired purpose*". Thus, according to this definition, humans are machines. However, we tend not to think of humans as machines because we have come to associate machines with man-made contraptions powered by motors. Nevertheless, like all other machines, humans are governed by the universal laws of thermodynamics. In short, they cannot create energy from nothing. Humans depend upon food energy to generate heat and useful work energy output (a process called metabolism). Although the human body can temporarily consume itself to meet its energy needs, the quantum of this converted energy can ultimately never exceed the total input of food energy.

Unlike man-made machines which need only consume energy while they are working, humans consume energy for the purpose of sustaining their existence even when they are not working. Figure 6.3 illustrates the energy requirements which the human body is called upon to meet.

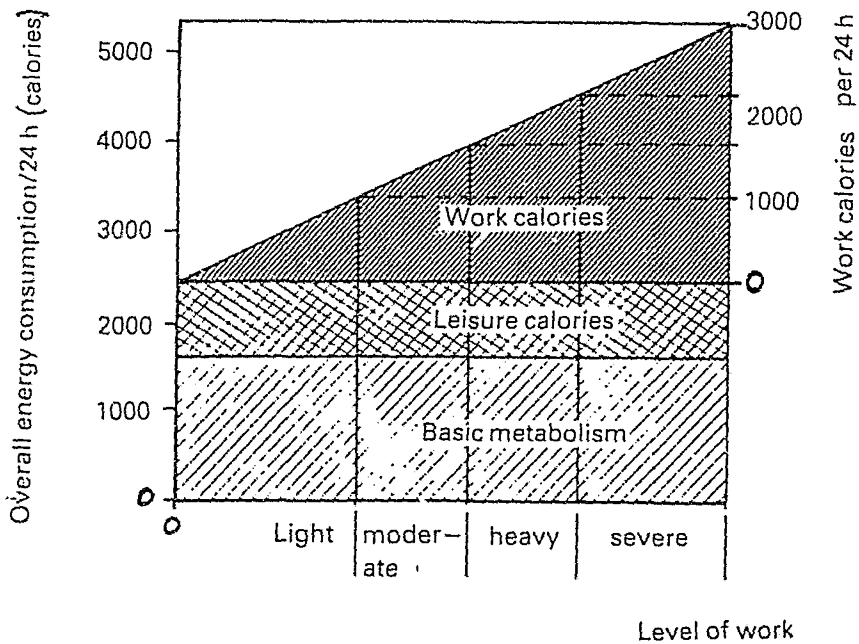


Fig 6.3 The different energy requirements in Calories (1 Calorie = 4.19 kJ) typically demanded of a human being. The energy available to do useful work is the difference between the energy metabolised less the basic requirements to sustain life. If too little food energy enters the body or if the basic energy requirements to sustain life are too great, then there will be no surplus energy to do useful work. (Source Grandjean [6.39])

Even when sleeping, humans consume energy and the minimum amount of energy required just to sustain existence is known as the 'basal metabolic requirement'. Added to this, humans also consume energy to perform certain essential daily tasks to replenish their strength and energy and remain healthy. This essential energy requirement fuels such tasks as fetching water, cooking, bathing, child caring and commuting to and from the workplace and has unfortunately been termed the 'leisure' requirement. (The term "leisure" is misleading since it seems synonymous with activities which are not very demanding.) Humans have a finite capacity to convert food energy into useful work over a given period of time[6.40-6.42]. This capacity is affected by gender and has been shown to progressively decline with age[6.39,6.43,6.44]; a deterioration characterised by a diminished aerobic and muscular capacity (see Figure 6.4). In healthy young adult males, it is generally accepted that the maximum quantity of energy which can be converted in metabolism (over a sustained period of more than a few weeks) is no more than about 20 MJ/day[6.40,6.41,6.42] (equivalent to the potential energy contained in about half a litre of diesel fuel). This is a surprisingly small amount of energy, since it includes the basal metabolic and 'leisure' requirements which may consume more than half of this energy if people have to gather firewood, carry water and walk a distance to and from their workplaces. Furthermore, the basal metabolism of diseased people is bound to be higher than in healthy individuals since their bodies must consume energy to fight the disease. Thus, the available energy to do useful work is the difference between the maximum energy which can be metabolised and the daily energy requirements. The only way of obtaining more useful work out of motivated, healthy and well fed workers, is to assist them in reducing their 'leisure' requirement.

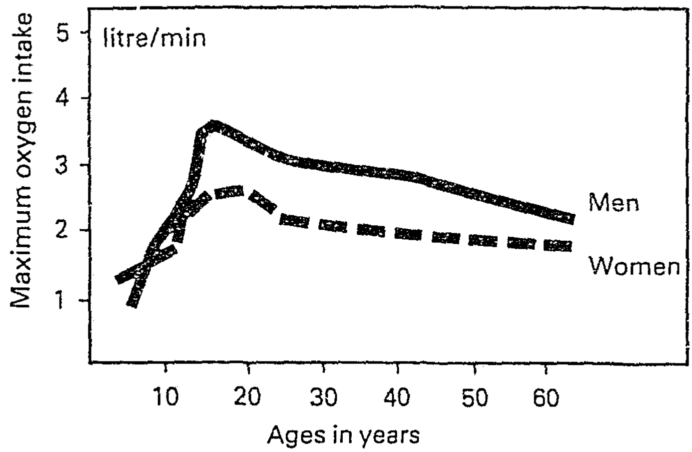


Fig 6.4 The diminishing relative physical work capacities (a function of their maximum oxygen intakes during a standard task) of men and women at various ages. In general, women have a lower capacity than men of the same age but this difference becomes less pronounced with age. (Source Astrand and Astrand)[6.39]

6.3.1 The relative efficiencies of human labourers and man-made machines

By means of an experiment conducted by the author[6.45] (see Appendix 4 for comprehensive details) the heart-rate respc ·· of a human subject, engaged in sub-maximal upper-body activity, simulating the mixing of concrete, was shown to correlate closely with both oxygen consumption and mechanical work output. Based on this correlation, the cost of buying human energy, in the form of manual labour was estimated in terms of well appreciated costs of diesel fuel and bread. Human energy was found to be at least 12 times more expensive than diesel fuel energy and its cost, in terms of equivalent loaves of bread, so dear as to raise doubts as to whether labourers could sustain themselves on the minimum wage of R7 per day, set by the National Public Works Program in 1994[6.11], let alone feed their dependents. These conclusions are conservative since it was assumed that only highly motivated male labourers in optimal health and nourishment toiled at their maximum capacity for the minimal remuneration of R7 per day. However, very few destitute South African workers are prepared to work for such low remuneration and it has been shown that their physical health and nutritional status is far from optimal. Thus, the actual cost of human energy could well be 20 to 30 times the cost of diesel fuel.

The competitive advantages of 'human machines'

Despite the dearness of human energy, human labourers have the following unique advantages over man-made machines:-

1. Versatility Unlike most man-made machines which have a very limited scope of application, human beings are extremely versatile. Given simple hand tools, a single human being can excavate, load, haul, and spread soil, mix concrete, fell trees, pump water etc. In practice, man-made machines are frequently deployed sub-optimally since the choice of machine for a particular application is determined by the availability of existing plant rather than what would be ideal.

2. Energy conversion efficiency The energy conversion efficiency in human-machines often surpasses that of other machines by a significant degree. A noteworthy example is the bicycle and rider combination which is universally regarded as the ultimate energy efficient transport system as illustrated by the schematic in Figure 6.5. This schematic is probably conservative since other calculations reveal even higher efficiencies. Williams[6.46] calculated that a cyclist on a modern racing bicycle can cover about 536 kilometres on the food energy equivalent of a litre of petrol. Mackenzie-Hoy[6.47] has estimated cycling to be about 40 times more efficient than motor cars filled to capacity with five occupants each. (Thus, it follows that motor cars with single occupants would therefore approach being almost 200 times less energy efficient than rider-bicycle combinations.)

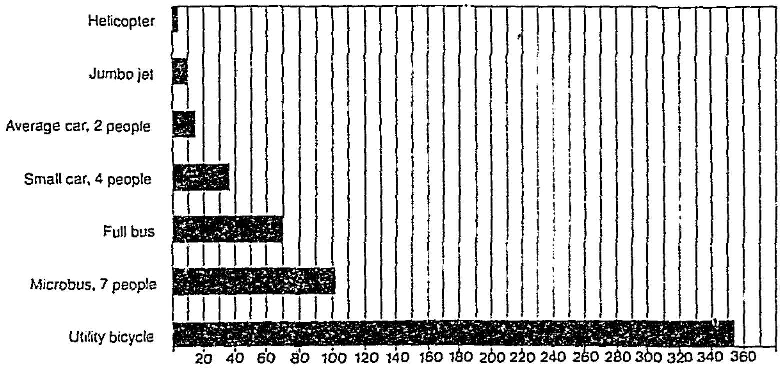


Fig 6.5 Passenger kilometres covered for the equivalent of a litre of petrol. Note that the bicycle referred to here is a utility bike: depending on conditions, a cyclist on a modern 'racer' could cover over 500 km on the food energy equivalent of a litre of petrol. (Source Noakes *et al.*[6.46] The Lore of Cycling)

Effectively utilised, the human labourer is no exception, and there are numerous examples where the energy efficiency of humans at the workface surpasses the best machinery. A noteworthy example to illustrate point is found in a reference[6.48] to a project conducted by the U.S. Army Cold Regions Research and Engineering Laboratory in Greenland during the summers of 1955 to 1957, in which a tunnel was driven through ice. One of the objectives of the exercise was to explore the most favourable methods of operation. The specific energy (a parameter which is the reciprocal of effectiveness) of each method of disengaging the ice is presented in Table 6.2. These values have been left in imperial units since it is only their relative differences which concern us. What is significant about them is that there is one exceptionally low value - Manual picking - which is nearly two orders of magnitude lower than the next best process (coal cutter, auger drilling and blasting). Bailey and Dean[6.49] provide a very convincing explanation for this great effectiveness of the 'human tunnel driving machine':-

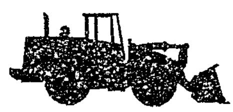
> *Efforts to produce practicable bit designs* (for conventional drilling machinery) *of greater effectiveness have been generally unsuccessful. As a result, faster drilling speeds have been achieved essentially only by the application of greater power to the hole bottom......There is no doubt that the very great effectiveness of the manual picking is due to the particular way in which the operator applies his effort. First he chooses the point of application of his every blow, as well as the force with which he will deliver it. Beyond this he operates in a remarkably versatile manner, not only is he able to indent the ice with his pick, but he is also able to pry with it. He undoubtedly seeks to develop a favorable geometry at the face and then to work in such a way as to maintain it. He works around hard inclusions and takes advantage of*

favorable failure patterns.......In general terms we must describe his very high effectiveness to the choices he makes in striking his blows. We have described this factor (for want of a better term) as 'intelligence'. Intuitively one can see the force of this argument by imagining what would happen to the effectiveness if the man had to operate in the dark!

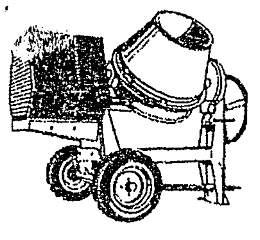
Method	E_s In. Lb/In.^{3}	E_s/σ_c	Remarks
Coal cutter	1740	3.5	Joy 10 RV machine
Coal cutter, auger drilling & blasting	410	0.82	Cut four sides of tunnel + cutter power & explosive power
Auger drilling	3160	2.9	2 in. holes
Drill & blast	1740	3.5	Drill power + explosive energy
Manual picking	23	0.046	Manpower, assumed 1/10 hp steady
Melting	42,000	84	Fusion power only

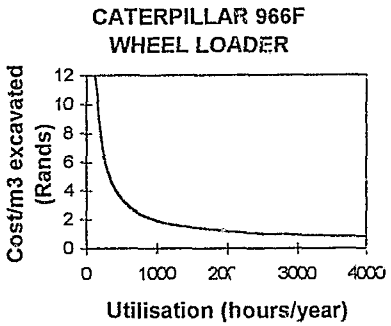
Table 6.2 Specific energies (E_s) (a parameter which is the reciprocal of effectiveness) for various processes of disengaging ice. (The unconfined compressive strength of the ice (σ_c) was of the order of 500 psi). Adapted from Dean[6.49].

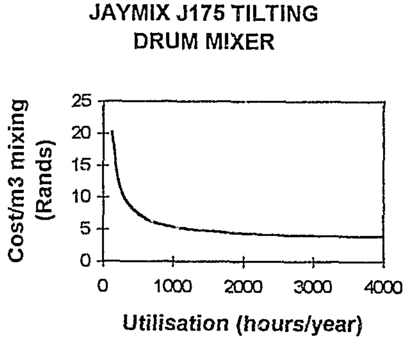
3. __Zero fixed cost of ownership__ Human labourers are not subject to any fixed costs of ownership such as capital acquisition, insurance and depreciation costs. These costs may form a significant proportion of the total cost per unit of production output from purchased plant. This is illustrated in Figure 6.6. where the relationship between annual utilisation and the cost per unit of production-output (computed in accordance with the method proposed by Caterpillar[6.74,6.75] Inc. Peoria, Illinois, U.S.A.), of two popular items of plant, is illustrated. The less an item of plant is utilised, the more significant are its ownership costs (as a proportion of the cost of produced output). For example, at a utilisation of 4000 hours per year, the ownership cost of the wheel loader (considered in Figure 6.6) represents 45 % of the cost of a unit of production-output. As its utilisation rate decreases, this ownership cost increases, until, at a utilisation of 125 hours pe [illegible] r, it represents 96 % of the cost of a unit of production-output. The current high cost of capit [illegible] th Africa is partly responsible for these significant ownership costs. It is interesting to note that the estimated owning and operating cost of the wheel loader considered in Figure 6.6 (assuming a utilisation of 4000 hours per year), is significantly greater (by 52 %) than the current South African hire rate of the equivalent item of plant (Caterpillar 966E). It is with this discounted hire rate that the human labourer must compete. However, it is questionable whether the South African plant-hire industry can sustain this subsidisation indefinitely.



966F Series II







Variables for South Africa (December 1998)		
	Caterpillar 966 wheel loader	Jaymix J175TSD tilting drum mixer
Delivered price (DP) (excl VAT)	R 1 437 994 (incl. tyres)	R 13 600
Residual value after 5 years	Nil	Nil
Depreciation	Straight line over 5 years	Straight line over 5 years
Cost of capital (@ 23% per annum)	R 190 163 (excl. tyres)	R 1 877/annum
Insurance cost (@ 2% of DP/annum)	R 28 760	R 272
Production output	420 m^3/hr @ 0.5 min. cycle time	3.15 m^3/hr
Job efficiency factor	75 %	75 %
Swell and bucket fill factors	Ignored	-
Fuel cost (diesel)	R 2.10/ℓ	R 2.10/ℓ
Operator's cost	R 20/hr	R 45/day
Operating cost including operator cost	R 156/hr (average load)	R 8/hr
Estimated owning and operating cost (assuming a utilisation of 4000 hrs/yr)	R 281/hr (including operator)	R 46/day (excl. operator)
Hire rate	R 185/hr (including operator)[6.77]	R 75/day (excl. operator)

Fig 6.6 The relationship between plant utilisation and the cost of production output for two popular items of plant assuming variables applicable to South Africa in December 1998. Computation of the estimated costs of production-output are in accordance with a method proposed by Caterpillar[6.74,6.75]. Information was supplied by Barlows Equipment Co[6.75], Babcock Construction Equipment[6.76] and the Contractor's Plant Hire Association[6.77].

6.4 DISCUSSION

The unemployed southern African labour-force appear to have few marketable resources other than their physical labour. Unfortunately, many of these labourers, including single women with dependants, the elderly without pensions and the partially disabled, are not easily disposed to sell even their labour. Furthermore, the health and nutritional status of the remainder of this population appears to be far from optimal. These impediments do not positively effect the population's capacity to perform hard physical work. Therefore, as a point of departure, it may be prudent to target the aspiring poor who are willing and able to perform heavy physical work and where possible, to include the less physically able to perform lighter tasks. However, regardless of what population is targeted, it is imperative that planners endeavour to utilise scarce human energy effectively. The following considerations are intended to promote an awareness of factors that might considerably effect on the effectiveness of human labourers.

6.4.1 Improving the effectiveness of human labourers and conservation of human energy

Before trying to identify physiological determinants which may influence productivity, it is important to note that the motivation of workers has been shown to be an important independent factor, capable of sometimes over-riding some physiological determinants and significantly influencing productivity[(6.50)]. Nevertheless, adverse physiological determinants will ultimately reduce productivity and human effectiveness.

Improving the health and nutrition of manual workers

Inadequate dietary intake results in restricted work capacity. Besides the First Law of Thermodynamics, there are several cases to substantiate this assertion. Gomez *et al.*[(6.51)] conclude that improved nutrition with increased dietary kilojoule and protein content resulted in significant weight gain and corresponding increases in maximal work capacity in rural adult South African males. Whitaker[(6.52)] attributes a steady increase in productivity among Natal sugar cane cutters (from an average of 2,2 tonnes/man/day in 1971 to about 4,0 tonnes/man/day in 1992) to stem significantly from their improved nutrition. Mainwaring and Petzer[(6.53)] recall their Rhodesian experience where undernourished recruits to the labour-force had to be treated for malaria and fed a balanced diet for a month before they built up the necessary fitness and stamina to perform the arduous manual work demanded of them. de Beer[(6.54)] reports similar experience in South Africa during the building of the RMC Maritsane Dam. In his case, two weeks of feeding the labour-force a balanced diet proved sufficient time for them to develop adequate stamina.

As noted previously, it remains doubtful that the current minimum remuneration of R7 per day is sufficient to sustain workers engaged in hard manual work. Moreover, this remuneration will probably be shared among many dependents. Hence, the question prevails:-

Can there be any better way of ensuring that a workforce is appropriately nourished, for hard manual labour, than by feeding workers on site with a balanced diet, in addition to remunerating them with some minimum wage?

Increasing the available energy to do useful work

As discussed previously, the available energy to do useful work is the difference between the maximum energy metabolised and the requirements for daily living. While the maximum energy metabolised cannot be increased beyond a finite limit, the requirements for daily living, particularly the 'leisure' requirements, can be reduced. The 'leisure' requirement of a typical Westernised adult is generally regarded[6.40,6.41,6.42] to be about 2,5 MJ/day. Given the lifestyle of developing African communities , their 'leisure' requirement is likely to be significantly greater. African women bear a particularly heavy burden in caring for their families. The extra effort and energy expended in caring for a larger number of dependent children, carrying water long distances, collecting firewood and cooking (tasks which are traditionally the African woman's domain), may be significant. Furthermore, most destitute workers in southern Africa walk to and from their workplaces, often significant distances from their homes. By assisting these labourers in the provision of child-care facilities, cooked food and transport to and from work or temporary accommodation near to the work-site, employers will make significantly more human energy and time available to do useful work.

Effects of extreme ambient temperatures and high relative humidity

Working under extreme ambient temperatures subjects the human body to additional stress since, in addition to doing mechanical work, it is also called upon to use energy to maintain the body temperature within a critical range. Heavy physical work produces lots of excess heat as a byproduct of metabolism which is useful in combatting cold. However, in extremely cold climates, such as arctic environments, significantly more energy is needed to sustain body temperature than is consumed for heavy physical work alone. The extremely high calorific dietary consumption of arctic explorers (26-30 MJ/day)[6.55,6.56] underlies this assertion.

In the warm climate of southern Africa, the elimination of excess heat is the predominant problem. This places a double burden on the heart since it not only has to supply the muscles with blood, but it also has to suffuse the skin to liberate the excess heat through the evaporative cooling of sweat. As relative humidity increases, this evaporative cooling effect is inhibited and the burden increases. The debilitating effects of temperature and humidity may be significant. This is evidenced in early studies by Mackworth[6.57] who considered the effects of incentives on performance in hot humid atmospheres and showed that even high incentives could not overcome the deterioration in output due to the effects of high temperature and humidity.

Various authorities have attempted to identify the temperature and humidity beyond which physical work becomes impaired. The early studies of Haldane[6.58] concluded that wet bulb temperature was the limiting factor and suggested an upper limit of 31°C in still air. The South African Chamber of Mines[6.59] recommended acclimatisation for workers who must work in conditions exceeding 27,5°C wet bulb temperature. The World Health Organisation[6.60] recommend a threshold for men and women of all ages of 30°C WBGT for light continuous work and 26,7°C WBGT (wet bulb global temperature) for moderate continuous work. Pepler[6.61], who studied the effects of heat on young acclimatised military men, concluded that they began to show a deterioration in performance between dry/wet bulb temperatures of 32,2/26,7°C and 35/29,4°C.

More recent studies indicate that gender, acclimatisation and race may be better specific indicators of the threshold of debilitating conditions for individual subjects. Differences between the thermal responses of men and women have received considerable attention, and while there is considerable disagreement over many details, there is general agreement that the adaptive response of women to heat is less efficient than that of men. Hertig and Sargent[6.62] found that women have a poorer sweat response than men and they caution that 'employers in hot industries should be aware of the increased risks to female employees'. It has been suggested that this may be in consequence of the fact that women have a higher thermoregulatory set point, a greater proportion of adipose tissue and a lower aerobic capacity than men[6.63].

Wyndham *et al.*[6.64] compared the physiological performances of white and black male subjects. Their findings indicated that before acclimatisation, the black males had a far superior physiological performance. They attributed this to the result of a natural selective pressure on a race native to the area, plus the fact that the black subjects were all labourers and would already have acquired some degree of acclimatisation through hard work in the heat.

In a study of Natal sugar cane cutters under moderate ambient conditions (10-20°C WBGT), Lambert *et al.*[6.52] have demonstrated the importance of ingesting adequate food and fluids during the working day to replace some of the energy expended and to reduce the fluid loss. They suggest that the actual amount of fluid that needs to be ingested can be estimated by relating fluid intake to each worker's weight loss during the working day. A weight loss of more than 3% (of a subject's body weight) during the working day is indicative that the worker's fluid replenishment is inadequate. This may ultimately lead to chronic fatigue with a negative effect on productivity[6.65]. In the case of their sugar cane cutters, several subjects lost more than 3% of their body weight during the working day despite ingesting 5,0 litres/day. Subjects who ingested 6,0 litres/day suffered much smaller weight losses. They predicted that this intake of 6,0 litres/day may have to be increased later in the cutting season, when temperature and humidity increase.

Mainwaring and Petzer[6.53] report their Rhodesian experience in labour-intensive road building in the extreme heat near Wankie during the years 1966-1968. They found that after introducing a work quota system with flexible hours, teams of labourers chose to work at the coolest time of the day, starting work at 04h00 and completing before midday. However, they emphasise the responsibility of management to carefully set out areas of work in advance to ensure that teams which wish to start early are not impeded in their efforts.

Load lifting, carrying and hauling

Work physiologists rank activities which involve lifting and carrying heavy loads, among the most strenuous forms of work and a prime culprit of lumbar distress[6.39]. Therefore, designers and planners of labour-intensive projects may realise significant savings if they take the trouble to harness the force of gravity to advantage. Simply positioning the batching plant and rock-pile uphill of the workface and stockpiling the cement and sand uphill of the batching plant, facilitates an easy downhill flow of material. By linking the stockpiles, batching plants and workface with straight and gently descending haul-roads, the effort required to push wheelbarrows can be virtually eliminated. Such an energy saving may be significant. For example, Figure 6.7 shows a batching plant and material stockpiled in the riverbed on the down stream side of the Maritsane Dam during its construction. A total of 5700 m^3 of RMC was cast, the mass of which was about 13,7 X 10^6 kg (assuming a density similar to conventional concrete). Assuming that on average, each cubic metre of this material was manually lifted about ten metres (that is about half the height of the finished wall), then a total of about 1370 MJ (the product of the RMC weight times the height) of human energy would be wasted. Assuming a conservative maximum work capacity of about 10 MJ/labourer/day and an energy conversion efficiency of about 50%, this would amount to about 274 wasted man days.

Similarly, by syphoning water from a higher altitude, the human effort required to facilitate its delivery for mortar mixing and curing can be eliminated. Not only does this provide light work for a physically impaired labourer, but the chances of achieving the desired degree of curing are greatly enhanced.

Recognising the consequences of over-exertion from lifting heavy objects, a number of organisations (such as the ILO[6.67,6.68]) have concerned themselves with setting standards for the maximum weights that individuals should be expected to lift. Unfortunately, many of these standards fail to take cognisance of relevant human variables (such as gender and age) and task variables (such as size and shape of object). Moreover, these maximum weights do not necessarily make most effective use of human energy.

Fig 6.7 An inappropriately situated batching plant near the river bed level downstream of Maritsane Dam. Note the wheelbarrow haul ramp up to the work-face. The human energy cost of positioning the batching plant at the level of the foundations of a structure this size is estimated to be about 270 man days. A more appropriate position would be above (at a higher altitude) one of the abutments.

According to Teeple[6.66], a load of about 35% of a subjects body weight is optimal if we measure energy efficiency in terms of transporting an object from a fixed point to some destination. However, in practice, the task of carrying usually necessitates an "empty" return journey which increases the total consumption of energy. Lehmann[6.40] has proposed, that under these circumstances, a larger load of 50 to 60 kg is the most efficient to carry (Presumably, Lehmann is referring to adult males). Cement bags are optimally carried vertically over the centre of gravity of the body (draped over the shoulder) so that the effort of balancing is minimised, and unnecessary static muscular work avoided. Unfortunately, the rough and irregular stones used in RMC construction are seldom as conducive to carry as bags of cement. They typically have to be lifted and carried with both hands in front of the body. This tends to overbalance the body and the corrective action subjects the abdomen and spine to much static muscular stress and moment respectively. Furthermore, rough terrain often precludes the use of wheelbarrows and necessitates these stones being carried significant distances. Therefore, the optimum weight of stone to be lifted and carried will be significantly less than an object with an ideal shape, such as a bag of cement. Kroon[6.69] has suggested that 25 kg borders the threshold of the maximum' weight of rock that a labourer can handle effectively. Croswell[6.70] has proposed that a mass of 32 kg borders the upper threshold of what a labourer can reasonably be expected to lift (unassisted) repeatedly as a day task. However, he qualifies that this is not to say that far greater loads cannot be safely manipulated with mechanical aids or load sharing. It is worth noting that Le Roy[6.71] attributes much of the poor productivity during the building of Balfour Dam to the awkward manual manipulation of heavy 80 kg precast concrete blocks, used as permanent formwork. An additional inefficiency in this project arose when the supply of rock near to the workface became exhausted and labourers were forced to gather alluvium from afar upstream and downstream. As a result of no planning, they were required to lug these boulders over unnecessarily vast distances to a few isolated stockpiles[6.71].

Evolution of manual construction methods and tools relative to other human achievements

The modem rider-bicycle combination, as mentioned previously, epitomises mans' ability to enhance the already efficient human machine. Two hundred years of gradual development through engineering, have made the rider-bicycle combination the most energy efficient means of propulsion known to man. The bicycle descended from the celeripede, a contraption resembling a horse with two wheels instead of legs and no steering. Forward movement and retardation were effected by the rider pushing with his feet against the ground. Through many refinements this machine gave way to a front wheel driven 'boneshaker' shown in Figure 6.8. In 1869, James Moore cycled his way to victory in the first ever 123 km cycle race from Paris to Rouen in about 10,5 hours at an average speed of 11,8 km/h [6.72]. Today amateur cyclists regularly cover similar distances in less than one third of his time. By comparison, a walker would take about five times as long and would burn about four times as much energy[6.46]. Moreover, an extension of the bicycle has facilitated numerous human powered flights, one of which succeeded in crossing the Aegean Sea[6.46].

In contrast to the evolutionary refinement of human powered propulsion, Figure 6.9 shows the labour-intensive activities of masonry construction in Mesopotamia during the third and second millennia BC[6.73]. Apart from the absence of wheelbarrows, there is apparently little to distinguish these manual methods of batching and mixing from those which abound many of our labour-intensive construction sites today (4000 years later). In an experiment[6.45] (comprehensively described in Appendix 4), a simple crudely constructed, manually powered drum mixer was evaluated and found to be more than twice as effective as mixing by hand on the ground. It consumed less than half as much human energy per unit batch of output and it could produce more than twice as much mortar in a given time, and of a better consistency. Particularly encouraging is the fact that this manual powered mixer was a first generation prototype. If the evolution of the bicycle is used as an indicator of the potential of a human powered machine for refinement, what further improvements might be possible of the manual mixer, or indeed, many other simple hand tools?

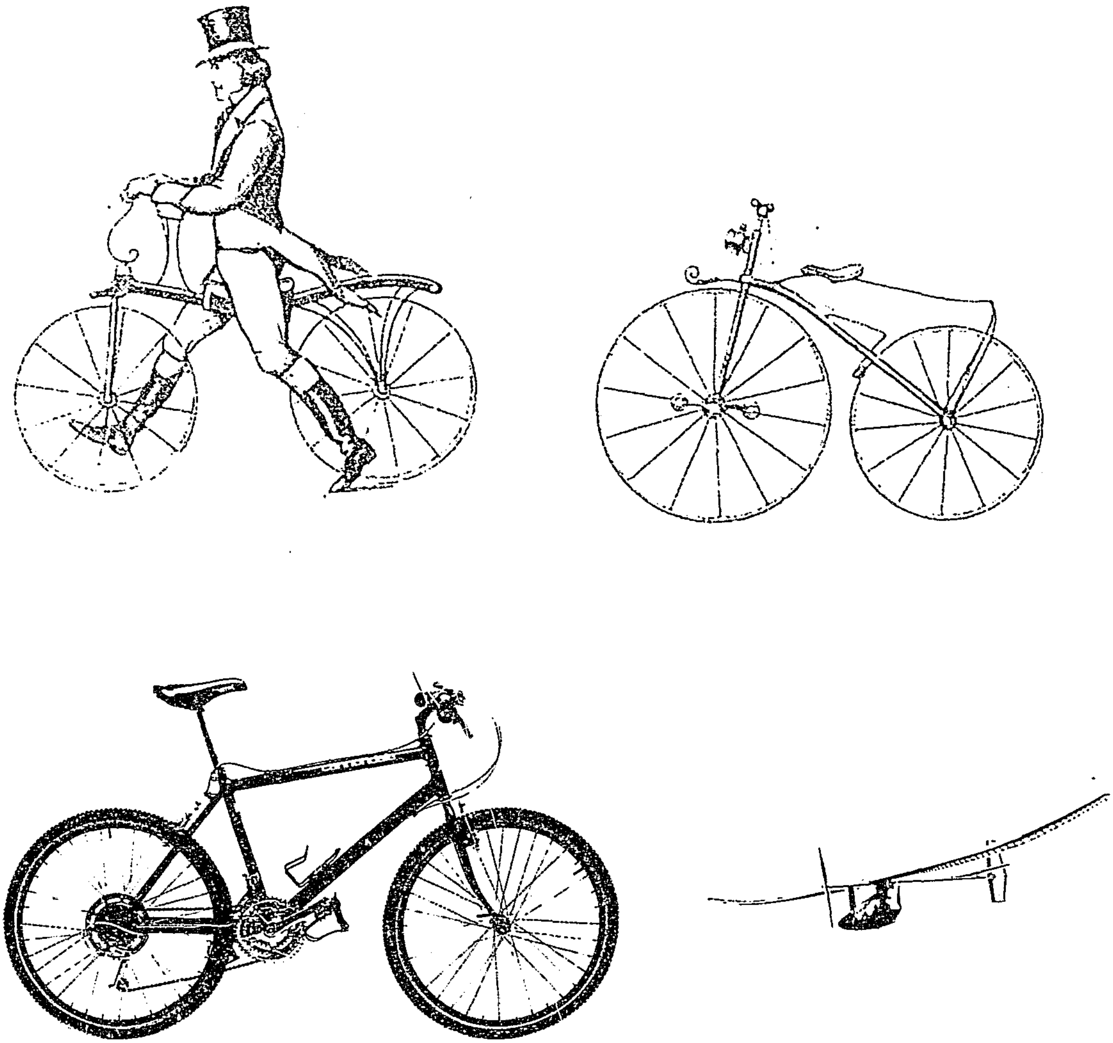


Fig 6.8 The evolution of the bicycle. Top left, the original celeripede (early 1800s); Top right, the 18 kg front wheel driven bone shaker of 1869 which James Moore rode to victory in the first 123 km cycle race from Paris to Rouen; Bottom left, the most efficient means yet devised to convert energy into propulsion, the modern workhorse: Bottom right, Massachusetts Institute of Technology's human powered aircraft Daedalus which kept aloft for almost four hours and flew from Crete to Santorini over the Aegean Sea in 1988[6.46].

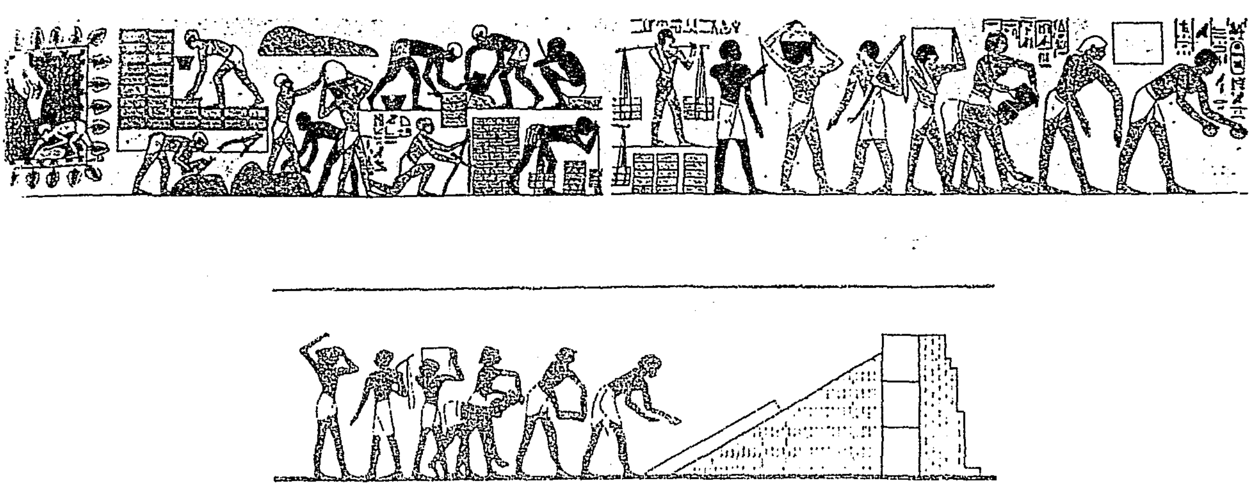


Fig 6.9 Mural paintings from Abd-el-Qurna which show the labour-intensive mixing of lime-sand mortar for the building of a temple in Ancient Egypt (1950 BC) (Source Larousse Encyclopedia of Ancient and Medieval History[6.73]). Apart from the advent of the wheelbarrow, the activity *of manually mixing on the ground appears to have changed little since the time of the pharaohs..*

6.5 CONCLUSIONS

The targeted southern African labour-force, who have few marketable resources other than their physical labour, has been identified. Among the most needy recipients of employment are many who are not well disposed to selling even their labour; including single women with dependants, the elderly and the partially disabled. Moreover, the health and nutritional status of the targeted population has been shown to be far from optimal and declining. These impediments do not impact positively on their physical capacity to perform hard manual work. Even at the best of times, the available human energy to do useful work is limited and consequently, if not efficiently harnessed, its economic cost is high. However, when compared to man-made machines, human labour is demonstrated to possess a number of competitive advantages including:- its versatility, its extremely efficient energy conversion efficiency and its independence of fixed cost economic inefficiencies. Recommendations to improve the effectiveness of human labourers include:- the provision of better healthcare and nutrition, a reduction of physically demanding 'leisure' activities, scheduling the most physically demanding tasks during cool periods, harnessing gravity to advantage and the promotion of hand-tool and human-powered machinery developments.

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CHAPTER 7

PROPOSED MATERIAL SPECIFICATIONS GUIDELINES FOR RUBBLE MASONRY CONCRETE STRUCTURES

7.1 INTRODUCTION AND SCOPE

The success of any structure ultimately depends upon the correct choice, and intelligent use, of its constituent building materials. Where possible, structural engineers ensure this durability through comprehensive specifications which limit the choice of available materials and prescribe their correct usage and/or minimum performance requirements. Conventional concrete materials' specifications typically oblige contractors to purchase materials which comply with standard specifications for use according to standard codes of practice - the compliance of which may be evaluated by standard methods of testing. However, designers of materials' specifications for RMC have a more difficult job since they have little currently recognised precedent and no conventional material and testing standards to depend upon. Furthermore, they are encouraged to use materials found in the immediate proximity of the structure, whose properties may not be accurately quantified and whose variability may be unknown. To many South African designers, this concept of making maximum use of locally sourced materials, with undeclared physical properties, is inadmissible. The ARMCO pressed steel culvert liner (a direct rival to the RMC arch bridge) is a case in point. Although less durable and more expensive than the RMC bridge, these prefabricated items are favoured in remote areas and appear in far greater numbers than RMC arches. For some reason, their specifiers apparently believe that the "imported" prefabricated article is superior to the locally hand-made equivalent.

Based on the theoretical and experimental investigations presented in previous chapters, as well as past practical experience, this chapter proposes some broad guidelines for specifiers aiming to achieve economical and durable hand-made RMC structures using maximum locally sourced materials and human labour. It is emphasised that these specifications are intended for general guidance and not as a substitute for the engineer's conscience. This is because the applications where RMC may be used are so vast, and the spectrum of usable ingredient materials so wide, that a specification which is ideal for one project may be completely wrong for another.

7.2 CHOICE OF BOULDERS

As mentioned in Chapter 2, masonry has proven its potential to outlast almost all other materials as evidenced by many ancient masonry structures which remain standing today. Studies[7.1-7.8] of the deterioration of ancient masonry structures indicate that the stone is generally more durable than the mortar and seldom responsible for structural failures.

7.2.1 Choice between freshly quarried rock and rock exhibiting naturally weathered surfaces

Where loose boulders occur in abundance near to the construction site, manual collection and stockpiling have cost saving and employment creating advantages. Several bridge structures[7.9] and at least two dams[7.10,7.11] have been built with alluvial[7.10] and colluvial[7.9,7.11] boulders in South Africa without incident. However, as boulders become scarce, blasting from nearby rock outcrops may become necessary, although perhaps not always ecologically acceptable. One advantage in specifying quarried rock is that mortar tends to bond strongly to its fresh and sound exposed faces, whereas naturally weathered rock faces often exhibit poor surface bonding characteristics. This was noted in Chapter 3 and by Alexander *et al.*[7.12] in studies of the bond of paste to various rock surfaces. Naturally (chemically) weathered surfaces of dolerite provide a particularly poor substrate for cementitious bonding. The weathering of dolerite results in the formation of a powdery skin, containing illite and montmorillonite clays which form a weak link in the bonding of the mortar to the rock. Small tensile and/or shear stresses can cause debonding. Figure 7.1 shows a typical failure where weathered skin dolerite rocks became detached from a bridge structure in the Northern Province of South Africa. Analogously, it is anticipated that the surface weathering of other felspathic rock families, such as basalts, gabbros and diorites, may similarly exhibit poor substrates for bonding. A simple test to indicate this condition is to wet the rock and rub its surface by hand as shown in Figure 7.2. The surface residue typically feels soapy as a consequence of the presence of clays. Unless such materials exhibit an exceptionally rough surface texture, they should be avoided.

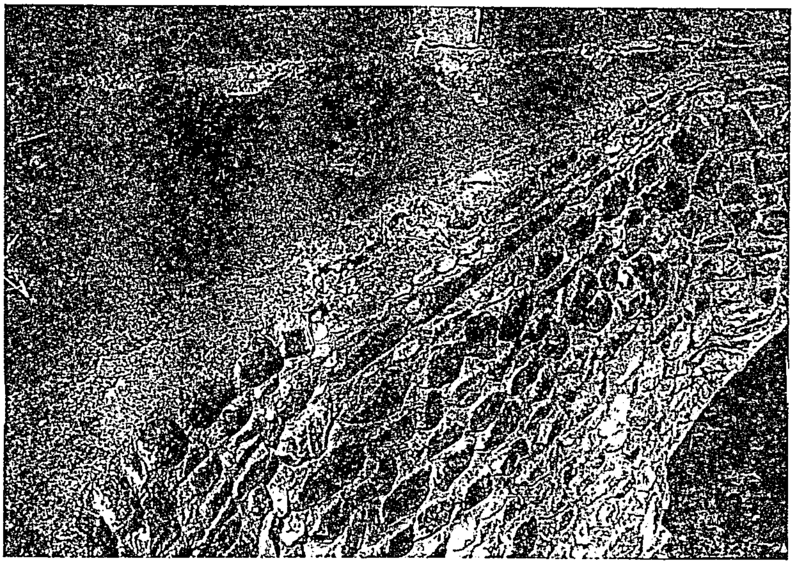

Fig 7.1 Minor damage sustained to the wing wall of a RMC bridge structure in the Northern Province of South Africa as naturally weathered dolerite rock, with poor bonding characteristics, became dislodged from the mortar matrix.

Fig 7.2 The weathered skin of dolerite rock contains illite and montmorillonite clays which offer a poor substrate for mortar bonding and are easily rubbed off with wet fingers. This residue feels slippery when wet.

7.2.2 Strength of rock

Kowalski[7.13] has argued that most alluvial stone, picked from water courses, is suitable for RMC construction since it has been subject to an automatic abrasion test which would otherwise have caused its disintegration. Similarly, Shaw[7.14] has argued that even colluvial stone automatically passes a 'quality assurance test' if it survives the handling, transportation and placement into a structure, which typically subjects it to being vigorously abraded against other stones several times as it is stockpiled, loaded and tipped.

However, there have been exceptions where rocks have survived these abrasive forces, yet have exhibited deficiencies. For example, rock types such as sandstones and granites, which consist of quartz grains cemented together by calcite and felspars respectively, weather by a process known as granular disintegration. Once the cementing material is removed or weakened, there is little to hold the grains together, and they may fall apart. Such materials may appear sound but are undesirable in RMC because they yield and crumble at low stresses. Initially, these materials yield at very low stresses as the empty spaces between the grains close. Thereafter, they typically exhibit increasing stiffness under increasing uniaxial compressive load as illustrated by the load-deflection plot in Figure 7.3. King[7.15] describes a simple test which may help to identify, and thereby avoid, the use of such deficient materials. Boulders are dropped from a height of 1.2 m onto a concrete slab (in the absence of which, presumably another boulder would suffice). Those which survive intact are acceptable. After a few demonstrations, it is usually possible to visually identify unsuitable material from a distance.

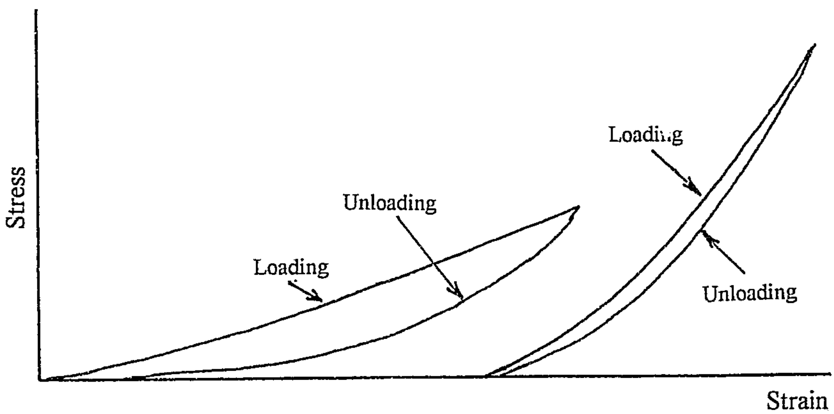

Fig 7.3 Typical load-deflection behaviour of unsuitable materials. Decomposed Bolubedu[7.9] granite (left) and crystaline Bakubung foyaite[7.14] (right) show increasing stiffness caused by closure of the spaces between the grains under increasing compressive load.

7.2.3 Optimum sizes of boulders

The question of an optimum range of boulder size for RMC is a complex matter which calls for engineering judgement and compromise after taking cognisance of a number of conflicting factors. Experience has shown that heavier stones (40 to 50 kg) are more resilient to being plucked from the surface of a structure by swift-running water than lighter stones[7.13].

As discussed in Chapter 2, historically, the primary incentive to incorporate large boulders in RMC appears to have been economic. The use of massive boulders afforded a reduction in the volume of mortar needed and this in turn reduced the costly cement content. Today, there is less incentive to save mortar. The cost of cement, in real economic terms, has decreased significantly over the past hundred years while its quality and consistency have greatly improved[7.16-7.18]. Therefore, a kilogram of modern portland cement inevitably goes further than the same quantity of cement manufactured during the last century. Several arguments, in favour of limiting maximum particle sizes to be substantially smaller than the gigantic inclusions used in the past, are listed below:-

1) **Human limitations for health reasons.** In harmony with the broader objectives of employment creation, it is preferable to avoid using mechanical lifting devices where human effort would suffice. Chapter 6 has reviewed the optimum range of masses to be manually lifted and shown that it is largely dependent upon the physical constitution and condition of the individual labourer. Le Roy[7.10] attributes much of the poor productivity during construction of the Balfour Dam to the fact that the labourers were frequently called upon to lift elements weighing 80 kg. He has subsequently proposed a mass of between 25 and 32 kg to border the upper threshold of what a labourer can reasonably be expected to lift and manoeuvre repeatedly without assistance; a view shared by Kowalski[7.13], Croswell[7.19] and Kroon[7.20]. However, this should not be interpreted to imply that heavier stones may not be safely transported by rolling, as opposed to carrying, or by the use of load sharing devices such as stretchers. Larger boulders which are too heavy to be manhandled in these ways can usually be reduced into manageable chunks with relative ease using a sledgehammer (see Figure 7.4).

Fig 7.4 The practice of reducing the size of unwieldy granite boulders into manageable chunks with a sledgehammer is common in Zimbabwe and was successfully adopted during the building of Maritsane Dam in South Africa. The granite boulders break relatively easily. Eye protection for the labourers is essential.

2) **Limiting maximum stresses and strength variability.** In Chapter 3, it has been shown that internal stresses, due to loading and thermal strains, increase as inclusion size increases and that variability of the mechanical properties of the composite also increases with increasing inclusion size.

3) **Ensuring phase continuity.** Difficulties in ensuring the maintenance of contact between the rock and the mortar matrix increase as the inclusions become unwieldy[7.8].

4) **Minimising permeability.** Permeability is likely to increase, particularly if bleed-water trapped at interfaces below large flat horizontal stones placed against the upstream face of water retaining structures causes discontinuities.

Maximum and minimum sizes of boulders are probably most practically specified in terms of mass. Typically, a range from about 1 kg to 25 kg has been used with success in the recent past[7.9-7.11,7.13-7.15,7.20] (see Chapter 3).

7.3 CHOICE AND ACQUISITION OF SUITABLE SANDS

River sands are commonly chosen for RMC construction, particularly bridges and dams, since they occur abundantly in many streams, thus obviating significant acquisition and transport costs. Furthermore, river sands tend to be clean and well rounded. Materials deposited by streams and rivers contain products of weathered rock, typically quartz, clays and rock fragments in various stages of decomposition. A river's ability to transport material varies as the sixth power of its velocity[7.21]. Therefore, a very slight change in the velocity of the current has a considerable effect on the nominal size of particles deposited (see Figure 7.5).

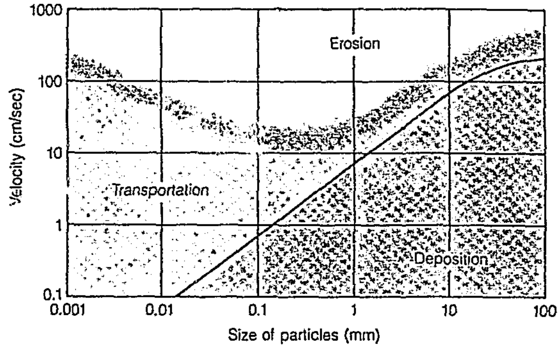

Fig 7.5 Threshold velocities for particle transport and deposition (after Hamblin[7.22]). The upper curve shows the range of minimum velocities at which a stream can pick up and move particles of given sizes. These threshold velocities are represented by a zone on the graph, not a line, because of variations including particle shape and density. The lower curve indicates the velocity at which particles of a given size settle out and are deposited. Note that fine particles stay in suspension at velocities much lower than those required to lift them from the stream bed.

One problem in excavating river sands, to satisfy an immediate need for mortar, is that they tend to naturally occur "bunch graded" (single size fractions tend to be deposited together where the flow is constant). For this reason, river sands can almost always be improved by blending with other materials to improve their grading envelopes. In attempts to improve the deficiencies consequent upon the somewhat limited grading distributions of their river sands, the Zimbabweans[7.23] favour blending them with pit sands, de Beer[7.24] has substituted imported fine filler sand and Shaw[7.11] has used a proprietary masonry cement containing finely ground limestone and an air entraining agent.

Many rivers contain an adequate range of material sizes in close proximity which can be interblended to achieve acceptable grading. Southern African rivers are often characterised by erratic flow and both grading and mineral composition of the stream bed deposits may show considerable variation, both laterally and vertically[7.25]. The flow velocity of a stream usually varies across its width (see Figure 7.6), at a curve (see Figure 7.7) and around an obstacle. These phenomena are not common knowledge. Indeed, de Beer[7.24] only discovered a deposit of fine filler material within the basin of the Maritsane Dam towards the end of the contract after much filler material had been imported from afar. Nevertheless, suitable material will not be found in every river. Sluggish rivers tend to possess an excess of fines in their bed-loads, whereas deposits in beds of swiftly flowing rivers may be completely deficient in fines. For example, during the building of the Likalaneng Weir, on a steep mountain slope in Lesotho, crusher sand had to be imported due to the complete absence of any sand in the bed of this rapidly flowing stream[7.24].

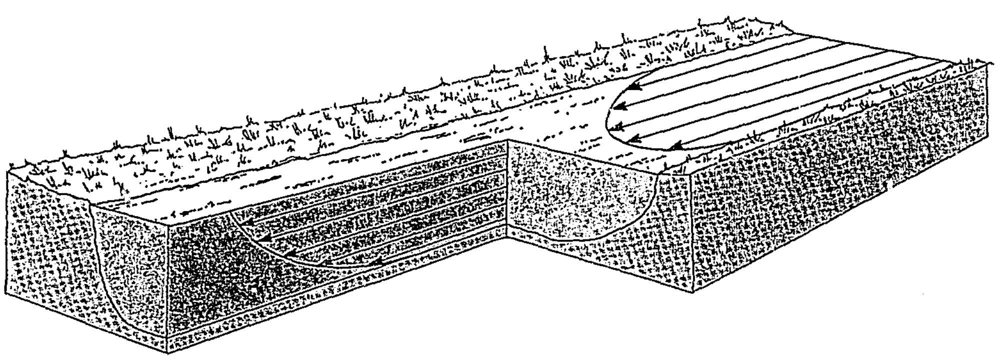

Fig 7.6. Variations in the flow velocity of natural stream channels occur both horizontally and vertically (after Hamblin[7.22]). Friction reduces the velocity along the sides and bed of the river. Therefore maximum velocity occurs mid-channel.

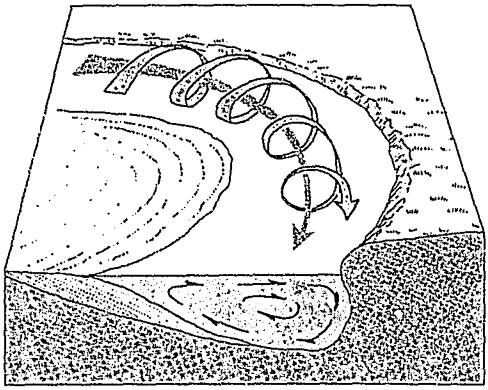

Fig 7.7 In a curved channel, water on the outside of the bend is forced to flow faster than that on the inside of the curve (after Hamblin[7.22]). As a result, coarser material is deposited on the outer radius and finer material is deposited on the inner radius.

Thus, where possible, it is proposed that specifications call for the contractor to excavate appropriate fractions and stockpile them prior to construction to encourage blending. This would have the further benefit of ensuring that the works can continue in the event of the entire riverbed becoming submerged.

7.4 CHOICE OF BINDER MATERIALS

Ancient RMC structures depended upon, and many of them continue to depend upon, lime (hydroxide of calcium and/or magnesium) as a binder for their mortars. Engineers in India have even used lime-clay-sand mortars in the construction of tall masonry dams[7.26]. During the past 200 years, significant advancements have been made in the field of binder technologies, the most noteworthy of which was the manufacture of portland cement. Straight portland cement-river-sand mixes often yield harsh mortars with poor water retention and a tendency to bleed. This is largely because river sands, even when blended, are deficient in fines. Bleeding in RMC has been observed (see Chapter 3) to cause large discontinuities between the matrix and the rock, particularly at the undersurfaces of large flat stones. Past efforts to reduce bleeding in RMC have included the use of fly ash[7.27] and air entraining masonry cements[7.11]. While they have reduced the extent of bleeding, neither of these measures would appear ideal. The reduced water requirement afforded by the improved rheological properties of the fly ash may be somewhat offset by the prolonged period over which the mix bleeds before it hardens. Air entraining masonry cements have been found to be more effective at arresting bleeding but there are concerns that the entrained air may compromise the matrix-rock interfacial bond strength[7.28,7.29]. Hydrated building lime (calcium hydroxide) has a large specific surface area which theoretically ought to reduce bleeding. An extensive review of lime literature revealed no quantitative data as to the extent to which limes might be effective in reducing bleeding. Consequently, a simple bleeding test, based on ASTM Standard Test Methods C 232-92[7.23] and C 940-89[7.24], was undertaken[7.32] (see Appendix 5 for a more comprehensive description of the test than that presented below) to investigate the potential of calcium hydroxide, when used as an admixture, to combat bleeding of cement:river-sand mortars.

7.4.1 Experiment to investigate the potential of lime as an admixture for RMC

River sand with properties presented in Table 7.1 was mixed with cement (CEM II B-V 32.5) in a 5:1 volume batch mix. Sufficient water was added to yield a collapse slump (water/binder ratio of 1,41). This mix was then divided into four, 15 kg batches. The first batch served as the control and calcitic hydrated lime ($Ca(OH)_2$) (SABS 523 type A2) was added to the other three batches by mass of cement (1%, 5% and 25% respectively) and mixed thoroughly into the mortar. Immediately thereafter, each batch was placed in a 10 ℓ polyethylene bucket (250 mm diameter) with a lipped seal lid to prevent evaporation of moisture. At hourly intervals, bleed-water was decanted from the surface and measured. The volumes decanted at the end of the third hour were encouraged to the surface by equal amounts of jolting. The results are recorded in Table 7.2.

Table 7.1 Properties of the river sand used for bleeding tests.

Properties		Grading analysis	
Relative density	2,582	Sieve size (μm)	Cumulative % Passing by mass
Loose bulk density (kg/m³)	1572	4750	100
Consolidated bulk density (kg/m³)	1712	2360	99
Fineness modulus	2,06	1180	89
		600	62
		300	32
		150	13
		75	5,1

Table 7.2 Volumes of bleed-water decanted from test specimens at hourly intervals (mℓ). The percentage lime additions are relative to the mass of cement. The percentages in parenthesis indicate the proportional reduction in bleeding at that time.

BLEED-WATER (mℓ) (PERCENTAGE REDUCTIONS IN BLEEDING)				
Time (Minutes)	Control (no lime)	1% Lime	5% Lime	25% lime
60	178 (0%)	102 (43%)	62 (65%)	19 (89%)
120	132 (0%)	115 (30%)	87 (52%)	30 (84%)
180 (Jolted)	180 (0%)	144 (26%)	108 (48%)	36 (83%)
Total Vol. (mℓ)	490 (0%)	361 (26%)	257 (48%)	85 (83%)

The results clearly indicate that the reduction in bleeding, afforded from an addition of as little as 1% lime by mass of cement, may significantly reduce the volume of overall bleeding.

In addition to reducing bleeding of RMC, this study demonstrated the potential of lime additions (as opposed to substitutions) to enhance the following mortar properties:-

1) Higher compressive strengths.

2) Greater tolerance to post-placement structural movement without cracking.

3) Reduced mortar permeability and therefore reduced efflorescence since efflorescent staining is proportional to the volume of solution transported through the matrix.

In view of these findings, it is arguable that lime should perhaps once again be included as an ingredient of RMC mortar mixes. The exact amount of lime needed to arrest bleeding will depend upon the amount of sub 300 μm particles present, the grading and the shape of the particles. An addition of between 5 % and 10 % by mass of cement is recommended as a point of departure. However, the addition of excessive lime may result in high mortar shrinkage as shown in Figure 7.8.

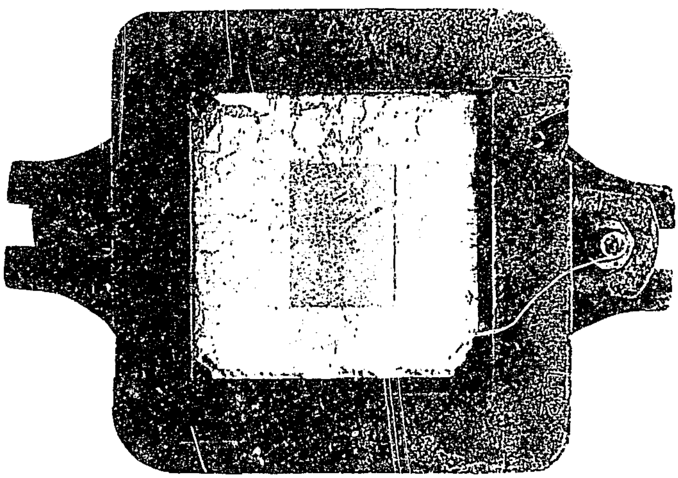

Fig 7.8 Dessication shrinkage of a 100 mm lime putty specimen. The linear shrinkage exceeds 5% and the volumetric shrinkage exceeds 15%.

Structures subjected to soft-water attack, particularly where the water is cold and running, may experience leaching of calcium hydroxide. In such cases, the use of dolomitic or magnesian limes containing magnesium hydroxide $Mg(OH)_2$ as opposed to calcitic lime is recommended[7.32] since $Mg(OH)_2$ is much less soluble than $Ca(OH)_2$. The use of slag extender is also recommended for this purpose as it produces a less permeable matrix. The Zimbabweans typically use a 50:50 portland cement-slag binder which they have proved greatly reduces the permeability of their structures[7.23].

7.4.2 Alternative binders for structures subject to low stresses

Since most typical RMC structures experience relatively small stresses, there may be opportunities to use binders other than commercially manufactured common and masonry cements. Many third world countries including Rwanda, Tanzania, India, Pakistan, Thailand and China have successfully produced, in small-scale operations, a variety of lime-pozzolana binders using rice husk ash, volcanic sands, burnt clay and brick powder[7.33]. In many cases these binders conform to performance standards[7.33]. There may be many benefits in using these materials in a developing country. Where the country does not have its own cement production facilities, there may be a saving in foreign exchange and a reduction in transport costs. Moreover, the employment per unit output of binder made in a small-scale alternative cement-making plant has been shown to exceed that of a conventional cement plant by a factor of 6 to 20[7.33]. There may also be a potential energy saving since the energy requirement to manufacture a kilogram of portland cement clinker is considerably higher than for lime or pozzolana. However, this may be difficult to realise since the latter is slower to develop strength and would therefore necessitate use in greater proportion to attain the same 28 day strength as conventional cement. Since alternative binders develop significant strength after 28 days, extended period strength specifications (say at 90 days instead of 28 days) are likely to boost their competitive advantage. Further research into the use of these binders for RMC may eventually result in a technology independent of material purchased from commercial manufacturers and therefore ideal for isolated communities without financial resources.

7.5 MORTAR MIXING, MIX PROPORTIONING AND THE IMPORTANCE OF A "KEEP IT SIMPLE" PHILOSOPHY

Most existing RMC projects have used simple nominal volume batching, typically in the range of 1:6 (binder to sand) for hearting masonry in low-stress areas, to 1:3 for masonry exposed to flowing water or more highly stressed masonry. Sims[7.1] has suggested that mixes richer than 1:3 benefit little from the additional binder and Roxburgh[34] has discovered a correlation between cement content and compressive strength at lower binder contents, indicating a law of diminishing returns, which appears to corroborate Sims' assertion (see Chapter 3).

Chemaly[7.23] cites Wild as emphasising the need to keep the mix proportions simple for the unsophisticated labour-force. Wild maintains that labourers cannot be expected to blend together anything more complex than his recommended one bag of cement and one bag of slag. Therefore, the addition of sophisticated materials such as silica fume and liquid chemical admixtures, which require precise proportioning and a particular mixing action to ensure homogeneous dispersion, is out of the question.

7.5.1 Manual mixing verses mechanical mixing of mortar

In harmony with the goal of employment creation it is desirable to execute a maximum number of activities manually, provided this does not compromise the quality and economic viability of a project. Large discrepancies in reported productivity amongst labourers engaged in the construction of RMC structures have been identified[7.41] (see also Appendix 4). Low production rates have been reported where mortar has been mixed on the ground by shovel, whereas higher production rates have been reported where mortar was mixed mechanically. Hand mixing on the ground by shovel was found to be an extremely inefficient and arduous activity, yielding little more than 2 m^3 per labourer per day (assuming the use of healthy, well nourished adult males and excluding the tasks of batching and delivery). In contrast, a simple manually powered mixer produced more than twice the output of mortar for less human effort[7.41]. Furthermore, the manual drum mixer produced more homogeneous mortar, as evidenced by the coefficients of variation of compressive strengths of cubes made from mortar produced by each mixing technique. Thus, it may be prudent to prohibit manual mixing by shovel on the ground in large projects and/or important work.

7.6 SPECIFICATION OF A MINIMUM ROCK CONTENT

The large rock inclusions, which are typically contiguous in RMC, serve a useful role in restraining post-hydration dessication shrinkage and thermal cooling strains. The practice of forcefully increasing the tempo of construction by manipulating the production of mortar towards an oversupply should be discouraged since it greatly increases the probability of an excessive volume fraction of mortar in the final composite. Excessive quantities of mortar interrupt this contiguity and render the structure susceptible to post-hydration cracking. Shaw[7.35,7.36] reports an instance where a crack manifested in the RMC Genadendal Dam in the Madikwe Game Reserve which he attributes to an excessively high mortar/rock ratio. Sims[7.1] reports a shrewd method once used to achieve a minimum volume fraction of rock in RMC products- *"If the volume of mortar exceeded 45%, the extra was considered to be waste and charged to the contractor."* Today, the cost of time and labour have risen relative to the cost of cement and consequently such a penalty may prove ineffective. Thus, it is probably safer to specify a minimum volume fraction of rock of about 50% which may be verified by large core testing at the discretion of the engineer. Practical experience has confirmed that volume fractions of rock of much more than 50% are very difficult to achieve (assuming the use of particles of a maximum mass of about 30 kg; typical of the so-called Zimbabwe material).

7.7 CLEANLINESS AND DRYNESS OF ROCK SURFACES FOR OPTIMAL BONDING CHARACTERISTICS

Where rock faces are contaminated by a layer of adhering dust or mud, interfacial bond is likely to be compromised (see Chapter 3). Other properties such as strength, particularly tensile strength, and stiffness may be correspondingly reduced and the composite will inevitably become more permeable. Specifications should therefore prohibit the use of material with dusty or muddy surfaces. de Beer ensured the cleanliness of the quarried granite, used to construct Maritsane Dam[7.37], by insisting it was high-pressure water blasted, immediately prior to transporting it to the workface. In addition to removing adhering surface dirt, this may also prove beneficial in cooling the rocks on hot days (which may get as hot as 55-60 ^{0}C in the sun in Johannesburg), thereby lowering the placement temperature and reducing the potential for post-placement thermal contraction (see Chapter 5).

With the possible exception of a few extremely absorbent rocks, such as some sandstones and shales, it is probably better to place stones dry rather than wet. Absorption of moisture by dry stones will tend to suck paste into its fissures, thereby enhancing bond.

7.8 EXPLOITING THE MATERIAL'S STRENGTH ANISOTROPY

Few recent RMC specifications even acknowledge that the material may exhibit strength anisotropy let alone attempt to exploit it to advantage. As a result, slender stones tend to be placed with their longitudinal axes and flat surfaces horizontal as this orientation occurs naturally under gravity. This has been observed to subject the material's weakest orientation to the principal compressive stress in the case of RMC arch bridges[7.9]. Given the unsophisticated nature of the workforce, coupled with the typical low stress levels experienced by most existing RMC structural designs and the superior strength of modern portland cements, this state of affairs may be justifiable. However, there may be portions of future structures which have the potential to experience relatively higher stresses. In such cases, the stones should be deliberately orientated with their longitudinal axes (maximum dimension) perpendicular to the principal compressive stress. In the case of arch bridges, this entails placing the intrados stones radially (normal to the arch curvature). In the case of arch dams, the maximum dimension of the stones must be orientated from upstream to downstream.

7.9 CURING

Methods of reducing moisture loss whilst maintaining the structure at a temperature above freezing, for a period after concrete placement, are well documented elsewhere[7.38] and many are suitable for RMC. Extended curing periods may be beneficial, particularly when extenders such as fly ash or slag are used since they are slower to develop strength. If RMC is not well cured, its potential properties, not only strength, but also impermeability and durability may be compromised. Experience has shown that the chances of curing being undertaken in practice are greatly enhanced if a reservoir is provided at sufficient altitude to permit water to be syphoned to the workface, rather than relying upon labourers to carry water in buckets.

7.10 CONSTRUCTION JOINTS

Most RMC structures are built as single monolithic entities without visible joints and cracks are the exception. The absence of visible shrinkage cracks may be due to the restraint afforded by large contiguous inclusions. Furthermore, the relatively slow tempo of construction and the low binder content permit significant dissipation of the heat of hydration which might otherwise give rise to thermal cracking. However, construction joints are inevitable at daily interruptions in casting and are often responsible for initial seepage in dam structures. A poorly contrived construction joint is a potential shearing plane and could jeopardise a dam structure.

Wegmann[7.39] has proposed that horizontal courses be avoided in water retaining structures and that the rubble be laid so that the stones break joints in all directions. Merriman[7.8] has recommended that large stones be left projecting above the general level at the end of a day's work to interlock with subsequent work as shown in Figure 7.9, thereby preventing the formation of shearing planes which might otherwise arise between two flat surfaces. There is wisdom in both these philosophies, provided these joint surfaces are inclined towards the principal stress trajectories to preclude tension opening the joint. Where there is a suspicion of inadequate curing of the previous day's work, the masonry surface should be "green-cut" (cut back) to remove any laitance and porous mortar and provide a good key. The debris from this green-cutting may be removed by blasting with compressed air or water.

Research by Brooks[7.40] has shown that the best bond is obtained when subsequent masonry is placed against a dry joint surface. The practice of applying a cement slurry coat, immediately prior to the addition of fresh masonry, may weaken the bond if the slurry dries before it is overlaid with new masonry. Therefore, unless it can be assured that the slurry coat will be scrubbed into the surface immediately before subsequent RMC placement, slurry coats should be discouraged.

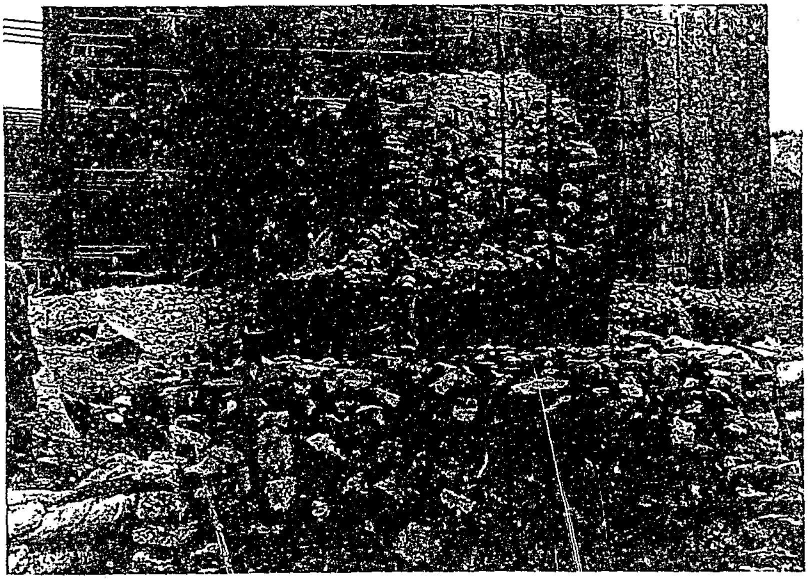

Fig 7.9 Stones left projecting above the general level of a day's casting to interlock with the subsequent work.

7.11 EMBEDMENT OF ANCHORS, DOWELS AND REINFORCING BARS

It has become common practice to anchor RMC structures to bedrock via reinforcing bars whose lower half is grouted into holes drilled in the rock, and whose upper half projects into the RMC structure (See section 8.6). Due to the large size of the boulders in RMC, little contact and mechanical interlock is possible between the rock and the deformations on the steel bars. Therefore, the pull-out resistance of deformed bars embedded in RMC is unlikely to be much greater than equivalent bars embedded in mortar alone. Consequently, it is proposed that steel bars are not cast directly into RMC. Instead, masonry should be built around the bars to form a cavity of at least 200 mm in diameter (radiating around the bar) and subsequently filled with conventional high slump concrete. This may also have an additional benefit of providing better protection against corrosion of steel bars.

7.12 PREVENTING THERMAL CONTRACTION CRACKING WITHIN THE COMPOSITE

The use of stiff rock, exhibiting a low coefficient of expansion may result in tensile failure at the mortar-rock interface or within the mortar matrix as a consequence of a large temperature drop below its placement temperature (see Chapter 5). Southern African dolerites exhibit these properties in addition to poor surface bonding characteristics if weathered. Thus, it is possible that thermal stresses, as a result of the mortar contraction being restrained by the stiff contiguous dolerite, may have contributed to the distress of the wing wall shown in Figure 7.1. Engineers wishing to use such materials for important work should therefore consider ways of reducing the risk of internal thermal fracture. For example, by specifying the use of smaller boulders, prohibiting the use of naturally weathered rock and promoting construction during the cooler months to limit the casting temperature.

7.13 CONCLUSIONS

1) The specification of materials for RMC has been a difficult job due to a complete lack of existing standards and the requirement to make maximum use of locally sourced materials.

2) With few exceptions, most rocks have been found to exhibit sufficient properties to make sound RMC. Blasted rocks with clean unweathered faces have been observed to offer a better substrate for mortar bonding than rocks with faces which have been weathered or soiled. Bond to all types of rocks may be compromised by a layer of adhering dirt.

3) The optimum range of rock sizes must take cognisance of human health limitations, flow of water past the structure, rock stiffness and the thermal coefficient of expansion of the rock.

4) Rocks may be orientated with their longest axes and flattest faces orthogonal to the anticipated maximum principal stress trajectories to exploit RMC's strength anisotropy to greatest engineering advantage.

5) River sands, excavated from a single location tend to be single sized. By excavating and stockpiling sand from different depths and different locations in rivers, better grading can be achieved.

6) Even well graded river sands, tend to lack water retentivity and bleed. Bleeding has been shown to compromise certain RMC properties. An experiment has demonstrated that the addition of a small proportion of hydrated lime, as an admixture, may reduce bleeding of RMC and enhance several other desirable properties.

7) Simple, straightforward mix proportioning is necessary to avoid errors when employing an unsophisticated labour-force.

8) Manual mixing of mortar on the ground using a shovel is inefficient and slow.

9) Specifying a minimum volume fraction of rock to ensure particle contiguity and strict adherence to proper curing will help to prevent post-hydration shrinkage cracking.

10) The faces of construction joints must be engineered and adequately prepared to prevent shear sliding failures.

11) Anchors, dowels and reinforcing bars should be surrounded by conventional concrete rather than RMC to enhance bond.

12) Great caution should be exercised when specifying the use of South African dolerite as this material may precipitate internal bond failure in RMC due to its stiffness and thermal stability coupled with its poor bonding characteristics if weathered.

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CHAPTER 8

PROPOSED GUIDELINES FOR THE DESIGN AND CONSTRUCTION OF RUBBLE MASONRY CONCRETE ARCH BRIDGES

8.1 INTRODUCTION

Arch bridges lend themselves to construction in RMC since their form efficiently exploits the masonry's mass and compressive strength thereby obviating the need to compliment its poor tensile strength with reinforcement. The durability of unreinforced masonry arches is evidenced by a number of ancient structures which remain serviceable today. Arch construction appears to have originated some 2000 years before the Roman conquest and the oldest stone arch bridges (built in 900 BC) survive at Smyrna, Turkey[8.1]. Most remaining masonry arch monuments show evidence of a serious effort to cut and shape the stones so that the joint planes were thin and perpendicular to the principal stresses (at least at the edges if not the core). However, there are exceptions such as the stone bridge shown in Figure 8.1.

The RMC arch bridge of recent times (pioneered by the Zimbabweans during the Rhodesian War of Independence from 1973 to 1980) utilises neither joint nor inclusion orientation to engineering advantage. A quagmire of confusion on the subject of arch analysis appears to torment many designers of RMC bridges. Indeed, it has been reported[8.2] that RMC arch bridges have been modelled as equivalent frames, necessitating the use of expensive reinforcing steel to "resist bending moments between the points of support". This chapter proposes guidelines aimed at best exploiting RMC for the provision of economically efficient and durable arch bridges.

Fig 8.1 Ancient pack-horse stone bridge in Watendlath Cumberland, England. The stones are not cut or dressed in any way but are orientated radially about the intrados which efficiently exploits the material's strength anisotropy.

8.2 CHOICE OF SITE LOCATION AND FOUNDATIONS

The first stage of arch bridge design involves the selection of a suitable site. Upon this single decision rests the ultimate success of the entire project. If a good site is chosen, the bridge may be built in harmony with nature and be economical; if not, it is liable to be washed away by the first flood. Ideally, such a site should offer the following:-

a) Bedrock beneath all arch abutments.

b) A straight section of the river or stream with well defined banks which will enable the bridge to cross perpendicular to its flow.

c) Moderately inclined banks which are neither too steep nor too shallow, so as to obviate the need for vulnerable and costly approach works.

Shelton[8.3] has cited the undermining of foundations by river flow (which accelerates around obstructions) as being the most common single cause of low level bridge failure in Zimbab