A STUDY OF RANDOM RUBBLE MASONRY CONSTRUCTION IN SRI LANKA

by

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Abstract

Random rubble masonry construction is a well proven and popular form of construction in Sri Lanka, mainly used for walls in contact with water and for walls where aesthetic considerations govern. Over the years, random rubble masonry construction skills have declined so much that many masons now consider it simply as an exercise in packing stones together to produce a wall. Impossibility of using the BS 5628, the masonry design code, for random rubble masonry with local stones has led to local designers opting not to design these structures except proportioning them by the middle-third rule and soil bearing pressure. In these circumstances an in-depth study was considered opportune.

The study consisted of a literature survey, survey of design drawings, dimensional measurements of stone sizes and mortar thickness of existing structures at 27 sites, compressive strength tests on wall panels built using stones from five different quarries, and subsidiary tests on properties of stones and properties of mortar.

The investigation resulted in formulating the design recommendations for random rubble masonry and ashlar (natural) stone masonry using local stones, and providing guide-lines for material selection, proportioning random rubble masonry elements, dimensional control of different stones that go into a wall, supervision of construction, and conduct of maintenance operations.

1.0 Introduction:

Random rubble masonry is a type of masonry construction (see Figure 1) which uses rubble stones of random sizes and shapes (an assortment of angular stones), excluding rounded stones (to prevent stress concentrations by point contact), bonded together with a mortar layer. These stones are much larger than concrete aggregates with: (a) smallest dimension ranging from 100 to 225mm; (b) large enough not to pass through a ring of 150mm diameter; and (c) weight limited (to about 25 kg) so that each stone can be lifted by a worker comfortably. The rough or uneven state of stones will develop a natural appearance to the face of the wall imparting it a high degree of durability as opposed to polished stones. In random rubble construction, it is not possible to foresee the exact bond pattern before actual construction as the mason selects the stones of different shapes and

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sizes, more or less at random, and places them in position to obtain a good bond, while restricting cutting of stones to sizing of the stone or removal of inconvenient corners with a chisel or hammer. However, it is not indiscriminate packing of stones, but bonding stones complying with certain broad principles\(^1\text{,}2\text{,}3\text{,}7\) in sizing, laying, bonding, breaking of joints, and finish in order that masonry develops adequate strength and presents a neat appearance.

Stone masonry has a long history of usage due to its availability and durability. However, higher cost of construction, higher cost of stones due to rising cost of production, transport as well as handling, and identification of applications where less durable and cheaper building materials can survive, have limited its current demand. Yet, random rubble masonry construction is a well proven popular form and its common applications are: (a) Non-loadbearing walls and loadbearing walls (up to three-storeys high) in buildings where aesthetic considerations govern or where stones are readily available and cheap in the locality; (b) Boundary walls and earth retaining walls (2.1m to 7.5m high) where aesthetic considerations govern; (c) Plinth walls of wall foundations where durability considerations govern as in water logged soil; (d) Abutments of road culverts with top concrete slabs and loadbearing elements of Hume pipes culverts; (e) Vertical sides (up to 1.8m deep) of surface water drains; (f) Vertical walls of manholes; (g) Small irrigation structures to control flow of water in irrigation channels (such as drop structures and weirs for flow measurement); (h) Constituent elements of small to medium span arch bridges (such as the arch, abutments, spandrel walls and wing walls); (i) Abutments and wing walls (up to 2.1m to 6.6m high) of small bridges; (j) Clock towers and water towers where aesthetic considerations govern; (k) Structures related to religion or culture (such as mosques, churches, kovils, temples and museums which should last a long period of time); (l) Outer leaf of cavity walls subject to rain penetration; and (m) Lighthouses to guide sea craft.

Materials used in random rubble masonry are stones and mortar. Widely used stones in Sri Lanka are charnockite, gneiss, and granite while widely used mortars are: (i) 1 cement : 5 sand (in contact with water, or multi-storey walls); (ii) 1 cement : 8 sand (above ground interior walls up to two-storeys high, or non-loadbearing walls); (iii) 1 cement : 2 lime : 9 sand (exterior walls above ground of strength similar to (ii) above); and (iv) 1 cement : 1 lime : 5 sand (exterior walls above second storey of strength similar to (i) above).

Most used stone masonry bond patterns in Sri Lanka are: (a) Ashlar stone (natural stone) masonry: It consists of rectangularly shaped stone blocks of the same height and same length in each course, where every stone is fine tooled on all beds, joints and faces, full and true. Very thin bed of mortar (3 to 5mm thick) can also be used;

(b) Random rubble (uncoursed) masonry: Here stones as they come from the quarry are used by the mason who selects blocks of all shapes and sizes, more or less at random, and places them in position to obtain good bond while restricting cutting of stones for sizing and for removal of inconvenient corners with a hammer, or a chisel and hammer. Due to absence of continuous horizontal courses of mortar, strength is about 50 to 75 percent of that of (a); and
Random rubble masonry with polygonal bonding: It consists of stones with no pronounced stratification roughly hammer-pitched into irregular polygonal shapes and bedded to show the face joints running irregularly in all directions. Out of the above types random rubble masonry is the most widely used, covering many applications. Following variations (see Figure 2) of random rubble masonry are also prevalent in Sri Lanka to obtain different architectural effects: (i) Flush mortar joint; (ii) Galleted mortar joint; (iii) Recessed mortar joint; (iv) Ribbon mortar joint; (v) V-grooved mortar joint. Types (iii) and (v) are not good where rain penetration is a concern, while (ii) and (iv) are best against rain penetration. Type (i) is the cheapest.

Normal tools used by a mason for brickwork or blockwork are: Plumb bob, normal trowel, string line, gauge rod, spirit level, four-fold metre rule, bevel, jointer, pointing trowel, hand board, wood float, straight-edge, mason’s square and linen tape. Except the gauge rod the following tools are required in addition, for stone masonry work: (a) Wooden mallet to tap a stone above a fresh mortar bed to ensure good bond without cavities and to eliminate point contact between adjacent stones; (b) Broad bladed chisel and hammer (2.5 kg) to cut stone to the desired shape and dimension; and (c) Sledge hammer (10 kg) to break large stones to the required size.

Advantages of random rubble masonry are: (i) It provides an aesthetically pleasing appearance; (ii) It requires no plastering or painting and appearance can be maintained by washing with water at suitable intervals of time; (iii) It can be used in contact with soil containing ground water due to its excellent durability; (iv) Quality control of materials is easy as defective stones can be easily identified; (v) Aesthetic appeal can be enhanced by the use of various jointing and pointing methods on mortar joints (see Figure 2); (vi) As compressive strength of stones are well in excess of the required wall strength, weak mortar can be used to minimise cost as well as to improve deformability; (vii) It can accommodate differential settlement well due to use of weak deformable mortars and restriction of stone size so that length is not greater than three times its height; (viii) Movements caused by moisture is insignificant; (ix) Amount of thermal movement is also small and vertical expansion joints 10 mm wide at 15 m spacing is adequate; (x) Repairs to either mortar or stones are not cumbersome to execute; (xi) It can utilize all dimensions of stones after required sizing; (xii) Lower porosity and water absorption reduce the risk of deterioration; (xiii) A stone wall can provide good thermal comfort in lower storeys of a building because its greater mass gives a high heat capacity and is therefore slow to heat up or cool down; (xiv) Low sound absorption due to its hard nature and good sound insulation properties due to its heavier mass, make it a good sound proofing material; and (xv) Efflorescence is unlikely to be a problem as any soluble salts in natural stones are leached out by water before the stone is quarried, and movement of soluble salts due to external causes is limited as local stones are not porous.

Disadvantages of random rubble masonry are: (a) Costlier than other alternative materials; (b) Consumes more mortar than other walling materials due to irregular size of mortar joints and numerous voids to be filled; (c) Due to absence of continuous horizontal courses, compressive strength of the wall is about 75% of a wall with horizontal courses (such as ashlar stone
masonry); (d) Difficult and time consuming to construct than brickwork or blockwork because: (i) there is more weight to handle; (ii) uneven surfaces make plumbing difficult; (iii) individual stones are hard to cut and shape; (iv) Heavy stones squash the mortar bed; and (v) stones jam in wrong positions and just refuse to fit in; (e) Unsuitable for use in areas of intense heat or where fire resistance is critical since most stones (except sandstone) are adversely affected by quick changes in temperature; (f) Non-uniformity of stones as regards size and shape, requires greater care in arranging stones to adequately distribute pressure over the maximum area and to avoid long continuous vertical joints; (g) Incorporation of services such as water and electricity on to a wall is difficult as cutting chases or fixing wall plugs are not easy; (h) Ferrous metal fixings even when galvanized or coated with bitumen[1] provide temporary protection from corrosion and may lead to staining of stones, thus requiring costly alternatives like copper, stainless steel, phosphor bronze and aluminium bronze; (i) To join old and new work[2] masonry should be raked so that stepping of raking should not be more than 45° to the horizontal; (j) Holdfasts of door or window frames should be embedded in concrete chases; and (k) Ends of beams or trusses should be supported on concrete or stone bearing pads of adequate bearing area.

2.0 Need for Research;

Current practice for random rubble masonry construction is to employ masons on payment per volume or length rather than per day which necessitates the masons to improve their productivity. Rather than cutting idle time and working faster, they have resorted to devise faster construction methods such as just stacking stones with little consideration for (i) stone size; (ii) bond on external faces; (iii) transverse bond; (iv) mortar consumption; and (v) minimum or maximum mortar thickness. Research is required to arrest this trend.

Very little time is allocated to teach construction methods of random rubble masonry (as opposed to brickwork or blockwork) in the training programmes of new masons, middle level technical personnel and engineers. Contract specifications rarely give detailed descriptions of the construction procedure. ICTAD specification[2] is not clear, and needs simplification, elaboration with figures, and improvement. Research is needed to disseminate knowledge from engineers downwards through the construction team.

BS 5628[3] does not help engineers even to obtain suitable design stresses approximately for local random rubble masonry, thus structural engineers are reluctant to design random rubble masonry. Research can rectify this shortcoming by producing design guidelines on local random rubble masonry.

Random rubble masonry construction is presently the most widely used stone construction method in Sri Lanka with ashlar (natural) stone masonry confined mainly to old structures. Hence BS 5628[3] design method based on natural stone masonry is unrealistic for local usage. Research can provide a more logical basis for random rubble masonry design.

Presently in Sri Lanka, design of random rubble masonry structures is usually confined to: (a) Foundation design to obtain base dimensions by limiting the soil bearing stress and ensuring overall stability; and (b) Comply with type designs or proportionately reduce stresses by middle-third rule in the rest of the structure. Theoretical basis of type designs is not known and any realistic proportioning of a structure demands the
knowledge of limiting stresses of the material. Research can establish design stresses and popularise the BS 5628\(^{9}\) design philosophy.

Random rubble masonry construction is different from brickwork or blockwork as: (a) Stones should be made to required dimensions and shape at site by the mason; (b) Mortar thickness should be controlled within wide permissible limits along the mortar layer; (c) Mortar bed can be in a direction other than vertical or horizontal; and (d) Longitudinal and transverse bonds do not just happen and mason should skillfully produce them. Research can highlight the need for greater care during construction by the mason and the importance of using additional tools like a wooden mallet, chisel and hammers.

Repairs to stone masonry structures require the mastery of methods to cope with cracking in the short term, and methods for replacement of decayed mortar or stone in the long term. Research can evolve techniques suitable for local use based on methods developed elsewhere.

In addition to above, to popularise random rubble masonry construction and to make it more efficient, clear guidance is necessary on following basic issues: (a) Standard wall thicknesses to be adopted; (b) Standard sizes of stones that are permitted for walls of above thicknesses; (c) Desirable varieties of local stones (such as charnockite, granite and gneiss) and how to identify them; (d) Bonding sequence considered desirable; and (e) desirable construction methods to maintain required quality of construction. In order to find solutions to above, and to demonstrate that random rubble masonry is not just packing stones above and adjacent to each other, a study on random rubble masonry was considered opportune.

3.0 Literature Survey:

The following conclusions were made from the literature survey: (a) Although many types of stone masonry are used around the world, those used in Sri Lanka are ashlar stone masonry (to a limited extent), random rubble masonry (uncoursed), and polygonal walling; (b) Stones to be used shall be hard, sound, heavy, fairly impermeable and free from decay, weathering and defects like cavities, cracks, flaws, sand holes, veins, patches of soft or loose materials, and free of crypto crystalline silica or chert, mica, iron oxide, organic impurities, calcium carbonate etc. Rounded stones shall not be used; (c) If a stone has a natural bedding plane, it should be placed in compression in walls and arches, and vertically in cornices with mouldings; (d) Sizes of various stones (facing, backing, bond, hardening, plum, chip and quoin stones) that go to make a random rubble masonry wall should satisfy various criteria\(^{1,2,3,7}\); (e) Stone is formed by combination of minerals, each of which is composed of inorganic chemical substances. Chemical constituents\(^{13}\) of charnockite, gneiss and granite are: SiO\(_2\), TiO\(_2\), Al\(_2\)O\(_3\), Fe\(_2\)O\(_3\), FeO, MnO, MgO, CaO, Na\(_2\)O, K\(_2\)O, P\(_2\)O\(_5\), CO\(_2\) and H\(_2\)O; (f) Minimum requirements for stones are\(^{9}\) a compressive strength of not less than 10 N/mm\(^2\) and a water absorption less than 10 per cent; (g) The mortar should be durable, workable, but not stronger than stone. It should set reasonably quickly to prevent point contact between stones, bond well with stones to prevent rain penetration, and be elastic to accommodate minor settlement in the wall; (h) Mortar joints can be finished by jointing or pointing. Jointing is preferred as it is economical and leaves the mortar undisturbed, but pointing allows different colours to be introduced and to minimise rain penetration by use of less porous mortar to a depth of 20mm from the
specifications are unsatisfactory for local conditions because:
(i) even for ashlar stone masonry block strength should be measured by testing a full scale stone block, which is unlikely to be possible with most compressive testing machines; (ii) For random rubble masonry as rubble stones are of different sizes, and an equivalent block cannot be identified without further guidance; and (iii) for random rubble masonry which is more widely used than ashlar stone masonry, relating wall strength to the latter is to specify tests for on unused material; (j) Deterioration of stone is caused by: rain (carbonic and sulphurous acids); contact with metals (brass, copper, unprotected steel, and zinc salts from galvanized steel); soluble salts (from soil, rain and sea breeze); frost (where present); thermal stress (difference in surface and inside temperature due to low heat conductivity); erosion (wind and water flow); lichen, mould and algae (acidic material secreted); and mutual decay (chemicals from rain and limestone attacking sandstone, as well as magnesium sulphate from dolomite attacking limestone). (k) The best way to preserve stone is to eliminate the causes of deterioration such as not to use limestone and sandstone together, not to let vegetable growth in mortar joints, not to use limestone in industrial areas, providing efficient water drainage from its surface, and cutting out soluble salt migration by capillary action; (l) Stone preservatives currently in use are: raw linseed oil (no discoloration, needs annual application); boiled linseed oil (blackens, lasts longer); wax in benzene (no reaction, penetrates inside the pores); barium hydroxide (prevents calcium sulphate attack by forming insoluble barium sulphate); calcium hydroxide (absorbs carbon dioxide to form calcium carbonate); silicon resins, silicogel and silicon esters in solvents (acts as water, repellants); and quaternary ammonium compounds, organo-tin compounds and sodium pentachlorophenate (control organic growth); (m) Moderately soiled stones can be cleaned by: washing with water (brushing, scraping or high pressure jet), abrasive blasting (sand blasting); chemical cleaning (hydroflouric acid or cleaners based on caustic soda); and mechanical cleaning (power tools with carborundum heads, rotary wire brushes or abrasion blocks); (n) Oil stains, iron stains and copper stains on stone can be removed by carbon tetrachloride, water and ammonia respectively; (o) Defective stones can be replaced by identical new stones or by plastic repair using a mixture of cement or other binder, aggregates chosen to simulate original stone, and water; (p) Fire causes disintegration of stones due to: (i) expansion of different minerals (quartz expands considerably); (ii) difference in temperature between different zones of stones; (iii) cooling of stones due to cold water (limestone above 800 °C becomes calcium hydroxide and if water is present becomes a powder due to slaking); and (iv) low heat conductivity of stones (binding material silicate improves conductivity); (q) Victoria stone (mixture of 1 cement : 4 crushed granite with surface hardened by silicate of soda solution) and Ransom stone (mixture of fine sand, silicate of soda and powdered marble with surface hardened by boiling in a calcium chloride solution) are popular artificial replacements for black stone and marble respectively; (r) In repair work, defective mortar joints should be raked out to a depth of 20 to 40mm and washed out to remove dust and to reduce suction during pointing; (s) Common causes of distress of stone masonry are: efflorescence, attack by acids, staining, heating and cooling, fire, vegetative growth, movements, structural failures, and frost action (where applicable); (t) Repairs to stone masonry can be one or
more of the following: removing efflorescence and stopping soluble salt paths, grouting dead cracks, stitching live cracks after underpinning or other suitable structural treatment, pointing defective mortar joints, replacing defective stones, replacing defective metal anchorages with stainless steel, removal of vegetative growth, cleaning the stonework, replacement of zones which cannot be repaired, providing protection from severe exposure, application of preservatives, and cleaning drainage outlets.

4.0 Formulation of the Experimental Study;

4.1. Selection of Wall Type:

For the experimental study, a 300mm thick flush jointed uncoursed random rubble masonry wall was selected for the following reasons: (a) Uncoursed random rubble masonry is the most widely used type in Sri Lanka; (b) Flush mortar joint (Figure 2) is the most widely used type locally; (c) The most widely used thickness of random rubble masonry is 300mm; (d) This wall thickness includes all the basic stone types (Figure 3) in a random rubble masonry wall; (e) This wall thickness can be used for many common applications such as plinth walls, single-storey and two-storey walls, retaining walls, side walls of surface water drains, abutments of road culverts, walls of small irrigation drop structures and top parts of wing walls of small bridges; (f) This thickness is neither too small nor too big for lifting, transport and testing; and (g) This wall thickness allows a mason to use all his skills which determine quality workmanship in random rubble masonry (see 4.3.9).

4.2. Methodology:

To decide on the methodology to be adopted for the experimental study, the different schemes considered were: (a) Testing of storey-high (full scale size in mm 300 thick x 600 long x 2700 high) 1/3 or 1/4 full scale model walls; (b) Testing of storey-high full scale walls (full scale size as (a)); (c) Testing of ashlar (natural) stone masonry block units (size in mm 300 thick x 400 long x 300 high); (d) Testing of random rubble masonry columns (size in mm 300 x 300 x 2700); (e) Testing of small cubic wallets 300 x 300 x 300mm; and (f) Testing of medium size wallets (size in mm 300 thick x 600 long x 600 high). The last proposal (f) was adopted for the following reasons: (i) Thickness of 300mm was in conformity with reasons given in 4.1; (ii) Height of 600mm allows the placement of one bond stone at the centre of the wallette as bond stones should be placed at 600mm intervals vertically and 1.8m intervals horizontally with adjacent courses of bond stones staggered. This height also makes capacity reduction factor 1.0, so that $f_k$ of BS 5628 can be found unaffected of slenderness effects; (iii) Length of 600mm allows the use of 2 to 4 or more stones in a course. It also restricts plumb stones to 1 per course, projecting about 150 to 200mm as recommended spacing is 1.0m. This length also gave a value for reduction factor for small area (=0.97) very close to 1.0; (iv) It is neither too small nor too big for easy construction, lifting, transport and testing; (v) This wall size will not require a special test rig for testing; (vi) Standard workmanship and standard bond pattern of random rubble masonry can be embodied entirely within this wall size; (vii) Wall size is such that effect of small experimental errors, if any, such as slight variations from verticality or development of small eccentricity are not expected to be very
significant; and (viii) Failure loads and deformations are conveniently measurable being neither too large nor too small.

4.3. Governing Variables and Their Control:

4.3.1. Thickness:

A survey of literature and design drawings as well as field measurements at 27 sites revealed that thickness can range from: (i) 225 to 900mm for walls and retaining walls in buildings; and (ii) 375 to 5500mm in retaining walls used for landscaping and wing walls in bridges. However, with the present specification for stones\(^2\) minimum thickness possible is 325mm, as the breadth of facing or backing stone is governed by the fact that it shall not be greater than three-fourths of the thickness of the wall nor less than 150mm, and since the stone size is 150mm to 225mm. This led to the identification of the need to change minimum stone size of facing and backing stones to 100mm from 150mm due to following reasons: (a) There are many existing applications in Sri Lanka (like plinth walls, top part of short retaining walls, loadbearing walls up to 2-storeys) which use 300mm thick random rubble masonry; (b) with the new size of backing and facing stones, reduction of wall thickness to 250mm is possible as strength or slenderness is no hindrance and this will lead to economy; (c) Wide use of 300mm thick wall successfully over the years has underlined the benefits of this proposal; (d) Purchase of random rubble stones will be made simpler as one size of 100mm to 225mm is sufficient, rather than purchasing two sizes of 150mm to 225mm and 100mm to 150mm in the approximate ratio 3:1; (e) Successful use of 100mm thick solid concrete blocks for many applications have confirmed the possibility of using facing or backing stones of size 100mm; and (f) Use of minimum facing or backing stone size of 100mm does not introduce a new stone size as already this size is used for hearting stones in the wall.

Hence in this study a minimum backing or facing stone size of 100mm was adopted to fall in line with current trend in usage. The thickness of a wall can now vary from 250 to 5500mm in steps of 25mm. Note that thickness of brickwork can vary in steps of approximately 102.5mm starting from 102.5mm, while corresponding values for blocks are 50 and 100mm: For this study a wall thickness of 300mm was selected for reasons given in 4.1, and was not varied during the study.

4.3.2. Height:

A survey of literature and design drawings as well as field measurements at 27 sites revealed that minimum height of a random rubble masonry wall or part of it at constant thickness can range from 225 to 1500mm. As the height of a backing or facing stone may vary from 100 to 300mm, the minimum height should be 300mm (1 course) and can vary in steps of 50mm. Note that height of brickwork can vary in steps of 75mm, while height of blockwork can vary in steps of 200mm. For this study a wall height of 600mm was selected for reasons given in 4.2, and was not varied during the study.

4.3.3. Length:

Length of a stone can vary from 150 to 480mm assuming that the maximum weight of a stone for two-handed lifting is 25kg and that the density of stone is 2900 kg/m\(^3\). Hence length of a random rubble masonry element can vary from 300mm in steps of 150mm to 15m (beyond which a 10mm expansion joint is required). Note that length of brickwork can vary in steps of 113mm,
while length of blockwork can vary in steps of 200mm. For this study a wall length of 600mm was selected for the reasons given in 4.2, and was not varied during the study.

4.3.4. Mortar mix:

Commonly used local mortar mixes for random rubble masonry are given in section 1. As most local applications of random rubble masonry are in contact with water (plinth walls, wing walls, retaining walls, drain sides, culvert abutments etc.), the mortar mix of 1 cement : 5 sand of mortar designation (iii) was selected for the study and it was not varied. However, to investigate the importance of mortar in random rubble masonry, one panel was constructed and tested without mortar.

Cement and water used in the study complied with SLSL 107(10) and SLS 522(11). Sand used complied with BS 1200(12) consisting of river sand free of clay, silt and dust, and passing through a 2.36mm sieve. Cube strength and water/cement ratio values of the mortar used were measured.

4.3.5. Type of stone:

For normal random rubble masonry work in Sri Lanka, preferred stones are granite, charnockite and gneiss. Stones preferred for special applications are: sandstone for fire resistant work; marble and sandstone for curved or ornamental work; granite, charnockite and gneiss for work submerged or intermittently in contact with water; and granite and sandstone for work exposed to smoke or chemical fumes.

It was originally planned to obtain granite, charnockite and gneiss from 5 quarries selected from Puttalam, Gampaha and Horana regions. Due to security problems and difficulties in transporting small quantities of stones over long distances, this proposal could not be implemented. Instead, stones from 5 quarries at Piliyandala, Horana and Bandaragama (see Table 1) were used in this study, and all stones were found to be charnockite. Stones selected complied with section 3(b) above. Stones purchased were identified using IS 1123(14), and tested for compressive strength using 50mm cubes in accordance with IS 1121(15). The specific gravity and water absorption were found in accordance with IS 1122(16) and IS 1124(17).

As regards durability, test methods given in IS 1125(18) and IS 1126(19) were considered, but were not done as charnockite, granite and gneiss were proven as durable over a long period of usage.

4.3.6. Dressing of stone:

Specifications(1,2,3,7) for stone masonry require that the bushing in the face shall not project more than 40mm in an exposed face, and 10mm on a face to be plastered. Dressing of stones used in this study complied with the former requirement.

4.3.7. Size of stone:

Facing stone and backing stone (Figure 3) should satisfy(1,3,7,20,21) the following dimensional requirements: (a) Length of stone (3 x height (similar to bricks to allow differential settlement); (b) 100mm (amended for reasons given in 4.3.1.) breadth on base 0.75 x thickness of wall; (c) Height of stone 300mm; (d) weight of stone 25kg (for two handed laying); and (e) Length 2 x breadth (similar to blocks). Lesser the height of stone, shorter is its length. Every effort should be made to use taller stones as well as stones closer to the maximum weight of 25 kg.
Bond stone (Figure 3) should be at least 150mm square at the face and shall run through the full thickness of the wall up to 600mm in thickness. For walls exceeding 600mm in thickness more than one stone may be used to run through the full thickness of the wall with overlaps of not less than 150mm.

Hearing stone (or interior filling) can be of any shape, but shall not pass through a circular ring of 150mm inner diameter. The thickness of this stone in any direction shall not be less than 100mm and the next shorter dimension should be greater than 150mm. Hearing stone should be laid nearly level with facing and backing.

Plum stone should satisfy the same dimensional requirements as for hearing. It is placed to project vertically 100 to 150mm either way at about 1.0m intervals to form good bond between successive courses.

Chip stone (or spall) is a small stone less than 100mm in the longest direction and shall be used to avoid thick mortar beds or joints and to ensure that no hollow spaces are left anywhere in the masonry. Chips shall not be used below hearing stones to bring these up to the level of face stones, but can be used to fill the interstices between adjacent stones in hearing and they shall not exceed 20 per cent of the volume of stone masonry. Chip stones are selected from broken pieces of stone during construction.

Quoin stone is of rectangular shape and shall not be less than 0.003m³ and quoins shall be set out and built up in advance of the main body of the rubble walling. Breadth should not be less than the height, and length should be greater than the breadth (but not greater than 3 times the height). Height of a quoin should be as tall as possible but not exceed 300mm. It should be as heavy as possible, but within approximately 8.7 kg and 25 kg.

The above stones can be purchased in the following forms: (a) Rubble stones of size 150 to 225mm (stones whose minimum dimension is greater than 150 and less than 225mm) and rubble stones of size 100 to 150mm (stones whose minimum dimension is greater than 100 and less than 150mm) and large enough not to pass through a ring of 150mm diameter with the ratio of volume of former to latter at 3:1; or (b) Rubble stones of size 100 to 225mm (stones whose minimum dimension is greater than 100 and less than 225mm) and large enough not to pass through a ring of 150mm diameter. Latter is preferred and in either case chip stones are obtained from breakages at site. From three quarries, stones were ordered by method (b) while from other two quarries, stones were ordered by method (a).

Unfortunately, irrespective of the method ordered, stones delivered did not comply with the order and all the stones were very much bigger. Considerable effort has to be expended to break the stones to the required sizes and specified stone sizes were used in the study.

4.3.8. Type of bond;

Various types of bond used in Sri Lanka are given in section 1. As random rubble masonry (uncoursed) is the most widely used type in Sri Lanka, only that type was used in the study so that type of bond was not varied.

4.3.9. Mortar thickness:

Joints in random rubble masonry(1,2,3,7) should be not less than 6mm thick in any part of the bed, and should be thick enough throughout to take up any irregularities of the stones without making any stone to stone contact.
Maximum thickness should be 20mm. When a joint is more than 20mm, it should be well packed with chip stones to control the mortar thickness within above limits. The above standard procedure was observed during the study.

4.3.10. Architectural features:

Commonly used finishes are shown in Figure 2. As flush mortar joint is the most widely used finish, it was adopted for the entire study.

4.3.11. Workmanship:

Important considerations\(^1,\(^2,\(^3,\(^7)\)\) that determine standard quality of workmanship are: (a) Selection of good quality stones without defects (section 3(b)); (b) Rejection of stones of rounded shape to avoid point contact; (c) For ease of lifting and placement, controlling stone size not to exceed 25 kg; (d) Dressing the stones to required size and shape (4.3.6); (e) Keeping the stones clean and free of dust, and wetting before laying; (f) Selection of good quality sand without impurities or deleterious matter (4.3.4); (g) Ensuring that sand used passes through a 2.36mm sieve; (h) Use of good quality cement and potable water; (i) Use of correct mix proportion of mortar (section 1); (j) Use of well mixed mortar at the proper workability and before on set of stiffening; (k) Fitting each stone to its adjacent stones well ensuring proper line, dimensions and verticality (or batter, if applicable); (l) Sandwiching adjacent stones with a mortar layer to avoid stone to stone contact and maintaining mortar thickness between 6 and 20 mm, using chip stones where necessary; (m) Ensuring that cavities do not exist within the body of the wall and mortar beds are well compacted; (n) Minimizing inclined mortar beds as far as possible during bedding; (o) Use of facing, backing, hearting, bond, chip, quoin and plum stones of specified sizes (4.3.7) properly to attain the required bond pattern (Figure 3); (p) Ensuring that bushing in the face does not exceed 40mm on an exposed face and 10mm on a face to be plastered; (q) Use of quoin stones of specified size and rectangular shape (4.3.7), and setting them alternatively stretcher and header at corners (Figure 3); (r) Setting up quion stones in advance, before the main body of the rubble walling; (s) Raising the masonry in the structure uniformly, and when masonry of one part of the structure has to be delayed, the work is raked back at an angle not steeper than 45° to the horizontal and not allowing toothing; (t) Laying stones so that their natural beds (when visible as in gneiss) are in compression or in other appropriate manner (section 3(c)); (u) Use of wooden mallet, chisel and hammer in addition to normal masonry tools such as trowel, plumb bob, straight-edge, string lines etc. (section 1); (v) Use of few large stones than many small stones; and (w) Facing and backing stones should have near horizontal bedding with any concavity upwards, but not downwards or sideways, so that cavities can be filled with mortar well.

These were implemented during the study so that workmanship is of the standard quality.

4.3.12. Age:

In accordance with BS 5628\(^8\) , age of the wall panel when tested was 28 days and this was extended to 35 days when circumstances required this extension.

4.3.13. Curing:

BS 5628\(^8\) recommends that test panels be covered with polythene sheets for a period of 3 days after construction and then left uncovered until tested. ICTAD
specification recommends that masonry work in cement or composite mortar shall be kept constantly moist on all faces for a minimum period of 7 days. IS 1597 recommendation is the same as that of ICTAD(7) except the following additions: (a) Green work shall be protected from rain by suitable covering; (b) Top of the masonry work shall be left flooded with water with the close of the day; and (c) Watering shall be done carefully so as not to disturb or wash out green mortar and use of a perforated spout may be suitable.

In this study masonry was cured by keeping it constantly moist by sprinkling water on all exposed faces for a minimum period of 7 days with curing commencing after 24 hours of construction.

4.4. Other Influential Factors and Their Control:

4.4.1. Replicates:

In accordance with BS 5628(8), two replicates were used for a wall configuration defined by a combination of variables.

4.4.2. Load application:

BS 5628(8) recommends that load be applied at 1 N/mm² per minute uniformly over the whole area of the top and bottom of the panel with two platens or crossheads, through which load is applied, restrained against rotation to produce a flat-ended condition. During the study these requirements were complied with except that load was applied at a uniform rate lower than that specified so that deformation can be measured, and this was expected to give more conservative results as dynamic effects are eliminated. Load was applied in increments, not less than 10, and at each stage, deformation was measured. Further, load at first crack, ultimate load, crack widths at each stage, and development of crack pattern were recorded.

4.4.3. Computation of $f_k$

BS 5628(8) method to obtain $f_k$ values from wall panel tests, which combines statistical techniques with limit state theory, was used in this study.

4.5. Experimental Study:

4.5.1. Test series A:

This test series (Table 1) dealt with wall panel tests. Nominal panel dimensions in mm were 300 thick x 600 long x 600 high (4.3.1 to 4.3.3). Load application and other measurements were done as in 4.4.2.

4.5.2. Test series B:

This test series dealt with properties of mortar used in the wall panels (Table 2). Mortar cubes of side 70.7mm were used, and water/cement ratio (decided by the mason to attain the required workability) was measured and recorded.

4.5.3. Test series C:

This test series dealt with properties of stones obtained from five different quarries (Table 3). Properties obtained were: type of stone used, compressive strength, apparent specific gravity, water absorption and apparent porosity.

5.0 Results and Analysis:

5.1. Test Series A:

Results are shown in Table 1 and the main findings are: (a) ultimate strength variation between each pair of panels, expressed as a percentage of their respective means varied from +3.4% to +16.9%. These show the consistency of the results for a material as
variable as masonry; (b) Wall without mortar had a large elastic range (Figures 4 and 5) in comparison to that with mortar. Due to lack of significant ductile range, wall without mortar fails without early warning and hence dangerous to use. Also E value of wall without mortar was very low (Table 1) and even construction was difficult as stones get dislodged as dead load increases; (c) Most of the cracking in a wall with mortar take place across the thickness by way of near vertical cracks, indicating the need to pay greater attention to bonding on planes parallel to thickness face; (d) Maximum crack widths observed, range from 0.3 to 2.0mm. These are small considering that in reinforced concrete 0.3mm crack widths are allowed in spite of its corrosion risk; and (e) Measurable crack widths (greater than 0.1mm) developed only when close to failure.

5.2. Test Series B:

Results are shown in Table 2 and the main findings are: (a) Mean compressive strength, mean density and mean water/cement ratio of 1 cement : 5 sand mortar were 4.62 N/mm$^2$, 1968 kg/m$^3$ and 1.134 respectively; and (b) Coefficients of variation of compressive strength, density and water/cement ratio were 29.5%, 4.9% and 7.7% respectively. Low coefficient of variation of water/cement ratio demonstrates the experience of the mason in preparing mortar of correct workability consistently. Low coefficient of variation of density demonstrates consistency in compaction of cubes. Coefficient of variation of compressive strength is not low, but acceptable for a lean mix using fine sand.

5.3. Test Series C:

Results are shown in Table 3 and the main findings are: (a) The required variation of compressive strength of stone (35.42 to 56.34 N/mm$^2$) was obtained from charnockite alone and, non-inclusion of gneiss and granite did not become a shortcoming of this study; (b) Low water absorption values (0.40 to 1.10%) indicated good durability of the stones and low apparent porosity values (1.02 to 2.88%) indicated that stones have good rain penetration resistance; and (c) Normally apparent specific gravity is used to select building stones. Apparent specific gravity values (2.56 to 2.63) were low compared to 2.7 to 3.0 reported in IS 1123 showing that local stones were less dense and of lower compressive strength.

5.4 Formulation of Design Recommendations:

As structural units (stones) neither have a specified compressive strength by the manufacturer nor are subjected to regular quality control by the manufacturer, $p_o$ of BS 5628 was taken as the mean compressive strength of all stones from a given quarry. As the concept of specified minimum site compressive strength of mortar is not used in Sri Lanka, it was taken as the characteristic compressive strength of mortar using test results of all the 30 mortar cubes, which was found to be 2.379 N/mm$^2$. Table 4 and Figure 6 show characteristic strength values of random rubble masonry ($f_k$) obtained in accordance with the statistical procedure of BS 5628 and above assumptions.

Characteristic compressive strength values of random rubble masonry recommended for use is given in Table 5. It was developed as follows: (a) Values corresponding to compressive strength of stone ranging from 30 to 60 N/mm$^2$ were obtained from Figure 6; (b) Value corresponding to compressive strength of stone of 20 N/mm$^2$ was obtained assuming a linear variation between the origin of Figure 6 and point corresponding to
compressive strength of stone of 30 N/mm²; and (c) Values corresponding to compressive strength of stone ranging from 60 to 100 N/mm² was obtained by keeping the value at 60 N/mm² from Figure 6 constant, as there is no evidence of compressive strength of masonry increasing with compressive strength of stone in this range as mortar compressive strength is very small (mean value 4.62 N/mm²). Same trend can be seen in Tables 2(b), 2(c), and 2(d) of BS 5628⁸ beyond a block strength of 35 N/mm². Further, the recommendations in Table 5 are in agreement with Mills²⁵ recommendation of 2.45 N/mm² for random rubble masonry with cement mortars.

In ashlar (natural) stone masonry, stone block size is not variable and is known. Hence, if a method can be found to relate compressive strength of stone cubes to that of blocks, BS 5628⁸ can be used. This is best done using the well known relation in concrete²⁴,²⁵,²⁶,²⁷ that the compressive strength of a cylinder (height/diameter = 2.0) is equal to four-fifth of compressive strength of a cube (height/side =1.0). Based on this well known relation for brittle materials, a correction factor (k) to be applied to compressive strength of stone cubes (h/d=1.0) to obtain compressive strength of stone block (h/d = h₁/d₁) is given by

\[ k = 1.2 - 0.2 \left( \frac{h_1}{d_1} \right). \]

Compressive strength of stone block is equal to the compressive strength of stone cubes modified by the correction factor (k). Once compressive strength of stone block is known, BS 5628⁸ recommendations can be used.

6.0 Main Conclusions:

Main conclusions made from this investigation are: (a) Important considerations that contribute to produce standard quality workmanship are listed in 4.3.11, and this can be used as a checklist by supervisory personnel; (b) Characteristic compressive strength of random rubble masonry recommended for use by structural engineers is given in Table 5. This recommendation is in agreement with those of Mills;²⁵ (c) To enable use of local stones in ashlar (natural) stone masonry, a correction factor (see 5.4) was developed to obtain stone block compressive strength from stone cube compressive strength, so that BS 5628⁸ design recommendations can be used directly; (d) A random rubble masonry element can be proportioned using the following information: (i) Thickness can vary from 250 to 5500mm in steps of 25mm; (ii) Height can vary from 300mm upwards in steps of 50mm; and (iii) Length can vary from 300mm in steps of 150mm to 15m (at which point an expansion joint is required); (e) Charnockite, granite and gneiss are the desirable varieties of stone and they can be identified using IS 1123¹⁴; (f) Recommended method for ordering stones from a quarry is to specify rubble stones of size 100 to 225mm (stones whose minimum dimension is greater than 100 and less than 225mm) and large enough not to pass through a ring of 150mm diameter; (g) Various types of stone such as backing, facing, hearting etc. should be sized as in 4.3.7; and (h) Guidance on repair of random rubble masonry structures is made available in sections 3(i) to 3(t).

7.0 Acknowledgements:

Technical assistance rendered by Mrs.D.R.Cooray, Technical Officer, during this study is gratefully acknowledged.
8.0 References:


Final Year Project Report, University of Moratuwa, Moratuwa, 1997.


<table>
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<tr>
<th>Quarry location</th>
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<th>Modulus of Elasticity (N/mm²)</th>
<th>Mean dimension (mm)</th>
<th>Failure load (Tonnes)</th>
<th>Area (mm²)</th>
<th>Ult.Strength (N/mm²)</th>
<th>Small area correction factor</th>
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*Mortar mix of all panels except A61 was 1 cement : 5 sand

No mortar was used in wall A61

# Mean of measurements at three levels.

**TABLE 1 - WALL PANEL TEST RESULTS**
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<th>Wall number</th>
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<th>Mean compressive strength (N/mm²)</th>
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**TABLE 2 - MORTAR CUBE TEST RESULTS**
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**TABLE 3 - RESULTS OF TESTS ON STONE**
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<th>Mean compressive strength of stone (N/mm²)</th>
<th>Mean compressive strength of mortar (N/mm²)</th>
<th>Mean wall ult. strength (N/mm²)</th>
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<td>3.0718</td>
<td>1.0</td>
<td>1.0</td>
<td>2.5598</td>
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<td>A22</td>
<td>1:5</td>
<td>35.42</td>
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<td>3.434</td>
<td>3.0718</td>
<td>1.0</td>
<td>1.0</td>
<td>2.5598</td>
</tr>
</tbody>
</table>

* Defined in BS 5628<sup>(8)</sup>
# $f_k$ - Characteristic compressive strength of random rubble masonry

**TABLE 4 - CHARACTERISTIC COMPRESSIVE STRENGTH OF RANDOM RUBBLE MASONRY ($f_k$ in N/mm²)**
<table>
<thead>
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<th>Mortar designation (cement:sand)</th>
<th>Mortar mix</th>
<th>Compressive strength of stones (N/mm²)</th>
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<td>20</td>
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**TABLE 5 - DESIGN RECOMMENDATION FOR CHARACTERISTIC COMPRESSIVE STRENGTH OF RANDOM RUBBLE MASONRY (N/mm²)**
FIGURE 1 - RANDOM RUBBLE MASONRY
FLUSH JOINT

CHIP STONE

GALLETTED JOINT

FACING OR BACKING STONE

RECESSED JOINT

RIBBON JOINT

V-GROOVED JOINT  □ MORTAR

FIGURE 2 - VARIOUS JOINTS IN A RANDOM RUBBLE MASONRY WALL
FIGURE 3 - VARIOUS STONES USED IN RANDOM RUBBLE MASONRY
FIGURE 4 - TYPICAL STRESS-STRAIN CURVE OF WALL WITH MORTAR

FIGURE 5 - TYPICAL STRESS-STRAIN CURVE OF WALL WITHOUT MORTAR
FIGURE 6 - VARIATION OF CHARACTERISTIC COMpressive STRENGTH OF WALL WITH COMPRESSIVE STRENGTH OF STONE