DEVELOPMENT OF NOMINAL MIXES SUITABLE FOR SMALL CONSTRUCTION SITES IN SRI LANKA

BY
P.T.R.S. SUGATHADASA
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SUPERVISED BY
DR. M.T.R. JAYASINGHE

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DECLARATION

I, Parana Thanthirige Ranil Shanaka Sugathadasa, hereby declare that the content of this thesis is the output of original research work carried out over a period of 15 months at the Department of Civil Engineering, University of Moratuwa. Whenever others' work is included in this thesis, it is appropriately acknowledged as a reference.

Abstract

Both strength and durability of concrete are now considered as significant issues for concrete structures. In BS 8110: Part 1: 1985, the improved durability of concrete is achieved by using mixes with higher strength such as Grades 25 and 30. However, a recent survey has found that volume batched nominal mix of 1:2:4 (20 mm) is still used in many construction sites in Sri Lanka, especially in the outstation sites. Though this mix gives 28 days compressive strength of 20 N/mm^2, the long term durability of this concrete specially when exposed to aggressive environment is questionable. This could be an undesirable situation which should be corrected with both short term and long term solutions. The concrete mixes such as 1: 1.5: 3 and 1: 1: 2 recommended for Grades 25 and 30 are also not often used since they are expensive. It is shown that these two mixes could contain about 375 kg/m^3 and 485 kg/m^3, respectively. These are quite high cement contents and hence indicated the possibility for reduction to make them more cost effective. However, in all these mixes, the fine to coarse aggregate ratio was maintained at 1:2 so that the same gauge boxes could be used at the site.

In this research, a cost effective short term solution is suggested to obtain Grades 25 and 30 concretes based on detailed experimental programme. It is shown that strengths of 25 N/mm^2 and 30 N/mm^2 could be obtained with volume batched 1:2:4 nominal mixes by adding extra cement. For Grade 25, 20% extra cement could be recommended. For Grade 30, it is 30%. This can be considered as a quite practical solution since an extra gauge box for the percentage increase in volume of cement could be used.

With the aid of sorptivity testing, it is shown that extra cement could give enhanced durability. This study was further extended to determine the effectiveness of silica fume with locally available fine and coarse aggregates. It is shown that silica fume could give strength enhancement with certain mix proportions. It could also give the same workability at a lower binder to water ratio. It could also reduce the sorptivity thus increasing the durability.

Key words: Nominal concrete mixes, compressive strength, sorptivity

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1.0 INTRODUCTION

1.1 General

Construction can be considered as one of the pillar industries in developing country like Sri Lanka. Construction industry contributes to about 7% of the Gross National Product of the country (Central Bank of Sri Lanka, 2002). Further, long term policies and programmes should have to be implemented to promote the national construction industry to support the growth of economy. However, many construction projects become notorious for quality shortfall. Concrete quality can be considered as one of the key factor as it is used in projects of different scales both urban and rural areas. Hence, improvement in quality of concrete is essential.

In Sri Lanka, reinforced concrete designs are carried out in accordance with BS 8110 : Part1 : 1985 which has specified higher strength concretes in order to achieve adequate durability (Dias,1991). Thus, the structural designs should be carried out for Grade 25 or 30 with Grade 25 being the minimum. These concrete strengths can be easily achieved with ready mix concrete or with weigh batching at sites. However, a survey carried out in year 2002 has revealed that about 45% of the construction sites in Sri Lanka still adopt volume batching with nominal mixes, such as 1:2:4 cement, sand and 20 mm coarse aggregates. Dias (1994) has also reported that volume batching was extensively used in Sri Lanka. There are two nominal mixes recommended for Grade 25 and 30 concretes such as 1:1.5:3 and 1:1:2(ICTAD Specification 1988). However, these are not quite popular due to the high cost. This creates an undesirable situation where designs carried out with Grade 25 concrete could be constructed with 1:2:4 nominal mix. If it happens, concrete would have a lower characteristic strength than envisaged by the structural engineer. On the other hand, lower strength concrete could be continuously used at the expense of long term durability which may lead to costly rehabilitation work during the expected life span of the structure.

Therefore, there is an urgent need to develop nominal concrete mixes that could be adopted economically to obtain Grade 25 and 30 concretes. Such a mix would be extremely useful in short term until Sri Lankan construction industry is developed to adopt either ready mix or weigh batching at majority of construction sites, irrespective of the scale. The development of such economical mixes was one of the objectives of this research study.

The building industry in Sri Lanka is responsible for the over exploitation of many of its natural resources. Excessive clay mining for manufacturing of bricks has led to many environmental problems such as lowering the water table, degradation of fertile lands etc (Ranasinghe, 1997). Excessive sand mining in many rivers has led to salt water intrusion and erosion of river banks. Excessive coral mining has led to severe sea erosion. One solution that can be suggested is to develop alternative building materials. Other could be the improvement of durability of new structures so that the life span could be enhanced. The use of microsilica in concrete could have applications in this area with the enhanced durability that it could offer for the concrete. Since most of the structures in Sri Lanka are still constructed with Grade 20 –30 range concrete, it useful to have a detailed experimental programme in that range of strengths with locally available aggregates.

Microsilica consisting of more than 90% of amorphous Silicon Dioxide has a quite high pozzolanic potential. This was first tested in 1947 in Norway and the large scale production was started in 1970s. The present use of concrete containing microsilica is over 5 milion m^3/year (Lewis, 2001). The term generally used for Microsilica in the concrete industry is silica fume. Microsilica concrete has been used in major projects either to produce high strength concrete or when enhanced durability was required (Lewis and Hasbi, 2001). Microsilica concrete has proved particularly beneficial in areas where the structures are subjected to severe environmental attack such as due to hazardous ground condition (Sulphate and Chloride attack), moisture exposure or physical degradation such as abrasion and erosion (Keck, 2001). The countries extensively use silica fume include United States of America, United Kingdom, countries in the Middle East, Hong Kong, Norway, Sweden, Denmark etc. Recently, India also started using silica fume in many large construction projects upon the realization of the advantages that silica fume could offer with enhanced durability. Therefore, it is useful to determine the quality enhancement that could be achieved by using the silica fume with the fine and coarse aggregates used in Sri Lanka. This was the other objective of the study.

1.2 Objectives

The main objective of the research are the following.

1. Development of economical volume batched concrete mixes that can be confidently recommended for Grades 25 and 30.

2. Determination of the effectiveness of silica fume with locally available aggregates to enhance the strength and durability.

1.3 Methodology

In order to achieve the above objectives, the following methodology was adopted.

1. A comprehensive literature review was conducted to determine the ways and means of improving the strength and durability of concrete.

2. The extend to which the volume batching used by the Sri Lankan construction industry was assessed with a questionnaire survey conducted among practicing engineers.

3. The possibility of improving the compressive strength of concrete by changing the cement content was investigated experimentally.

4. A detailed cost study was carried out to determine the cost increments associated with the proposed mixes when compared with 1:2:4 volume batched concrete. The cost saving relative to the currently recommended grade 25 and 30 mixes were also determined.

5. The possibility of improving the compressive strength and durability of concrete by the introduction of small amount of silica fume was investigated experimentally.

1.4 Main findings

1. The questionnaire survey revealed that about 45% of the Sri Lankan construction industry uses volume batched concrete to attain its concrete demand. This is very much significant in the outstation sites where ready mix concrete is not available.

2. It is possible to use 1:2:4 (20 mm) volume batched concrete with 20% and 30% extra cement by volume to obtain Grade 25 and 30 concretes, respectively. It is prudent to use a reasonable quantity of water so that the slump will remain in 50 to 60 mm. However, even with higher water cement ratios also, the above mixes gave sufficient strength. For these mixes, it is useful to have well graded aggregates.

3. Silica fume in 5% to 10% by weight of cement could enhance the strength and lower the sorptivity of concretes having Grades of 20, 25 and 30. It is also shown that the reduction in sorptivity could be achived either by increasing the cement content or by using silica fume. The research study indicates that with the type of aggregate used in Sri Lanka, silica fume could be used to improve the desirable properties such as strength and impermeability. Therefore, it would be possible to explore the possibility of using silica fume with higher strength and also ready mix concrete in future.

1.5 Arrangement of Thesis

The second chapter of the thesis covers the literature about concrete technology and the use of silica fume for producing concrete.

The third chapter includes information about a questionnaire survey carried out among practicing engineers to assess the usage of volume batched concrete in the Sri Lankan construction industry.

The fourth chapter explains the experimental investigation carried out in the laboratory including compressive strength test and durability tests.

In the fifth Chapter, compressive strength results and sorptvity results were presented. These were used to develop suitable guidelines.

Chapter 6 gives the conclusions and recommendations for future work

Chapter 2

2.0 LITERATURE REVIEW

2.1 Concrete

Concrete and steel are the two most commonly used structural materials. They sometimes complement one another, and sometimes compete with another so that the structures of similar type and function can be built in either of these materials. Concrete is made from cement, aggregate and water with the occasional addition of admixtures. Concrete has a proven track record as a successful material in the construction of highest towers, the longest tunnels, the deepest shafts and the largest man made structures, and in conditions as extreme as the Arctic tundra and Middle Eastern desert (Masterton et al; 1997).

The invention to overcome the problem of the low tensile strength of concrete by providing steel reinforcement was the starting point for concrete to become the leading construction material in this century. It was realized that steel will not corrode, even in out door environments, when embedded in sound concrete (Schiessel, 1996).

2.2 Concrete mixes

Different concrete mixes such as designed mixes, prescribed mixes (done as weigh batching), nominal mixes (mostly done as volume batching) are used to meet the needs of construction work. In particular the concrete should have the following (Schacklock, 1974).

1. Comply with the specification requirement for structural strength which is usually stated in terms of the compressive strength of standard test specimens
2. Have satisfactory durability in the environment in which the structure is placed
3. Have a satisfactory appearance in those situations where it is exposed to view
4. Be as economical as possible.

2.2.1. Nominal mixes

Following the practice first established many years ago, concrete mixes are still sometimes specified in terms of volumetric proportions. The proportions of cement: fine aggregate: coarse aggregate are in terms of the bulk volumes of the individual materials. (i.e. for grade 20 concrete 1:2:4, for grade 25 concrete 1:1.5:3 and for grade 30 concrete 1:1:2). According to the ICTAD specifications (1988), the minimum cement contents for the Grade 20, 25 and 30 concrete are 320 kg, 405 kg and 552 kg per m^3 of volume batched concrete respectively. (These values are taking into account the cement bulking as well). Volume batching is difficult to control and nominal mix specifications provide no control over water content, so this type of specification should not be used unless site condition make it necessary (Barnbrook et al; 1976)

Experience also showed that allowance had to be made for the bulking which occurs with fine aggregates when they are damp. It is generally accepted that most concreting sands will bulk on average by about 25%. However, coarse aggregate do not bulk to any significant extent. The allowance can be increased for finer sands and decreased if the moisture content of the sand is unusually low (Shacklock, 1974).

Shacklock (1974) also mentioned that the quantity of water in the nominal mixes are judged so as to give a concrete of suitable workability for the work in hand. The fact that the required amount of water affects the final properties of the concrete very considerably, and that the quantity varies with both the selected workability of the concrete and the maximum size of the aggregate, shows the extreme weakness and the imprecision of this type of specifications.

In practice, nominal volumetric mix proportions are often associated with a particular concrete strength which is checked by the taking of test specimens. This association of the prescription form of specification with a performance requirement leads to a difficult and often unworkable specification (Shacklock, 1974).

2.2.2 Specified mixes

BS 5328: Part 2: 1991, recognizes four methods of specifying concrete mixes. A designed mix is specified by the designer principally in terms of strength, cement content and water cement ratio; compliance relies on strength testing. A prescribed mix is specified by the designer in terms of nature and proportion of mix ingredients; the concrete producer simply makes the concrete 'to order'. The assessment of mix proportions is used for compliance purposes, strength testing not being routinely used. The use of prescribed mix is advantageous when particular properties of concrete, for instance with respect to its finish or abrasion resistance, are required. However, a prescribed mix should be specified only when there are sound reasons for assuming that it will have the required workability, strength and durability.

A standard mix is based on ingredients and proportion fully listed in BS 5328: part 2: 1991 for several values of compressive strength up to 25 MPa, measured on cubes. The fourth type of mix is the designated mix, for which the concrete producer selects the water cement ratio and the minimum cement content, using a table of structural applications coupled with standard mixes. This approach can be used only if the concrete producer holds a special certificate of product conformity based on product testing and surveillance, coupled with certification of quality assurance.

Standard mixes are used only in minor construction such as housing. Designated mixes, although they can be used for strengths up to 50 MPa, are limited in application to routine construction. It is therefore, only in the selection of designated and prescribed mixes that a full knowledge of properties of concrete can be used (Neville, 1996).

2.3 Strength of concrete

Strength of concrete is commonly considered its most valuable property, although, in many practical cases, other characteristics, such as durability and permeability, may in fact be more important. Nevertheless, strength usually gives an overall picture of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. Moreover, the strength of concrete is almost invariably a vital element of structural design and is specified for compliance purposes (Neville, 1996).

The properties of in situ concrete are subject to considerable variability, because it is not a factory produced construction material such as steel, for example. The principal factors that affect the properties of concrete are mix proportions (especially the cement content), slump achieved (primarily depend on the water content) compaction during placing and curing after casting. The first two factors represent concrete mix constituents, and taken together will be characterized by the water / cement ratio, which is by far the greatest single influence on concrete production. However, this composite index is separated into mix and slump because the latter have more practical significance for concrete production and placing. Compactions and curing can be considered as workmanship factors.

The characteristic strength of the concrete should be specified at one age only. Unless specified otherwise, the strength test should be carried out at an age of 28 days for concrete made with a Portland-type cement (Barnbrook et al; 1976). Under normal conditions adopted in Sri Lanka, a standard deviation of about 8 is usually used for concrete mixes. This gives a current margin of about 13 N/mm^2. This means, when Grade 20 concrete is needed, under laboratory conditions, a strength of about 33 N/mm^2 should be obtained as the mean strength. However, it is stated that this current margin could be reduced by about 3.5 N/mm^2 when nine cubes were tested (Barnbrook et el. (1975)). Thus, the current margin required could be considered as 10 N/mm^2 when 9 cubes were tested. The current margin of 10 N/mm^2 is also confirmed by Dias (1991) as well

One of the major problem in making specifications for Sri Lankan practice will be to answer the question as to whether Grade 20 concrete, which is the most widely used grade in Sri Lanka, is permissible or not. Most modern codes of practice specify a minimum Grade of 25 for durability purposes if strength is measured by cube or equivalent cube strength. However, recent specifications drawn up for Sri Lankan practice – ie the Model Code and the ICTAD specifications have continued the use of Grade 20 concrete, probably basing their recommendations on the now outdated CP114 and CP 110 respectively (Dias,1991).

On the other hand, the use of Grade 20 concrete can not be rejected outright, because environmental conditions in Sri Lanka are probably less harsh than those in the UK or

Australia, for example. Furthermore, most concrete surface in Sri Lanka receive a mortar rendering, which provide additional protection. Finally, structures built out of Grade 20 concrete have not performed too badly. Hence, it may be permissible to continue the use of Grade 20 concrete, especially if it is shown that this does not violate the spirit of BS 8110 which is the code used for the design of concrete structures in Sri Lanka (Dias, 1991).

2.3.1 Mix constituents

Concrete is made from cement, aggregate and water with the occasional addition of an admixtures. There is some variety in the properties of cements, even between cements of the same type but made from different raw materials and the variation in properties possible in natural and manufactured aggregate is almost limitless. Thus, concrete is always a heterogeneous material with variable properties. The section outlines the typical properties required by, or inherent in, concreting materials.

2.3.1.1 Cement

In Sri Lanka, Portland cement manufactured by cement corporation is mostly used for construction work and it shall be is accordance with BS 12(2). At present, cement is allowed to be imported which again should be complied with BS 12(1). Hence one can assure that the strength and workability of concrete related to water / cement ratio and aggregate / cement ratio as in mix design charts are acceptable as for as local cement is concerned (Samarasinge et al; 1987).

Ordinary Portland Cement (OPC) and Rapid Hardening Cement satisfying BS 12 and ASTM C150 (Specification for Portland cement) can be used for producing high strength concrete. However, different brands of OPC will have different strength development characteristics because international standards allow variation in chemical composition and fineness within certain limits. Also the performance of chemical and mineral admixtures can be affected by variations in cement characteristics. Therefore, when choosing Portland cement for use in high strength concrete, it is important to examine carefully its fineness & chemical compositions (Jayanandana et al; 1998).

2.3.1.2 Aggregate

The term aggregate is used to describe the gravels, crushed stones and other materials which are mix with cement and water to make concrete. As aggregate form bulk of the volume of concrete, the selection of suitable material is important.

Of the materials in concrete, aggregate is the most variable. The overall grading of the aggregate affects the amount of water that must be added because 'fine' grading require more water than 'coarse' grading to obtain the same degree of workability. Aggregate particles which have sharp edges or rough surface, such as crushed stones, need more water than smooth and rounded particles to produce concrete of the same workability. It may be necessary to increase the cement content of a mix made with crushed aggregates or irregular shaped gravels to allow water to be added in order to make the concrete sufficiently workable without reducing the strength below the required level. However, due to interlock between aggregate particles, a crushed aggregate concrete may have higher strength than a smooth or rounded aggregate concrete with the same water / cement ratio, and this extra strength may be sufficient to offset the effect of the extra water.

As the maximum size of the aggregate is reduced, the cement content of the mix will need to be increased to give the same workability with the same water / cement ratio. This is because the surface area of aggregate to be wetted is greater with the smaller aggregate size. The fine and coarse aggregates should be proportioned to obtain the required workability with the minimum amount of water. Badly proportioned constituents require an excessive amount of water to give adequate workability, and this will result in concrete of low strength and poor durability. Moreover, aggregates should be hard, durable, firm, appropriately cleaned and suitably graded. The presence of harmful substances such as dust, mud, organic imparities, chlorides or any other harmful substance should not be in larger amount than allowable limits.

2.3.1.3 Water

Mixing water for concrete is usually required to be fit for drinking, or to be taken from an approved source. This is to ensure that the water is reasonably free from such impurities as suspended solids, organic matter and dissolved salts, which are frequently contained in natural water and which may adversely affect the properties of concrete.

Water is the most consistent of the constituents of the concrete but water quantity, and in particular the water / cement ratio, is most important for the production of concrete of consistent strength. The amount of water used should be the minimum necessary to give sufficient workability for full compaction of the concrete. When deciding how much water to use, allowance must be made for absorption by dry or porous aggregates and for the free surface moisture of wet aggregates.

2.3.2 Curing

The setting and hardening of cement depend on the presence of water. Drying out, if allowed to take place too soon, results in low strength and porous concrete. At the time the concrete is placed, there is normally an adequate quantity of water present for full hydration, but it is necessary to ensure that this water is retained so that the chemical reaction continues until the concrete has thoroughly hardened. If curing is efficient, the strength of the concrete increases with age; this increase is rapid at early ages and then continues more slowly for an indefinite period. Correct curing increases the impermeability and durability of the concrete, which is particularly important when it will be subject to water pressure or severe environmental conditions (Barnbrook et al., 1976). Curing increases resistance to abrasion; effective curing is thus most necessary for floors and other surfaces subject to wear. Continuous curing from the time the concrete is placed helps to ensure a hard, dense surface and to reduce the risk of crazing and dusting (Barnbrook et al; 1976).

More specifically, the object of curing is keep concrete saturated, or as nearly saturated as possible, until the originally water filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. In the case of site concrete, active curing stops nearly always long before the maximum possible hydration has take place (Neville, 1996).

Powers in 1947 showed that hydration is greatly reduced when the relative humidity within the capillary pores drops below 80 percent. This was confirmed by Patel et al in 1988.

Meyer in 1987 has clearly established that the effect of curing on strength is a function of specimen size. Dias in 1994 has recommended that the curing is very significant main factor for durability characterize by sorptivity. Results obtained by Rasheeduzzafer et al in 1989 indicate that inadequate curing has a more dramatic effect than inadequate compaction on the time required to initiate corrosion and on the severity of sulphate attack. Dias (1994) has recommended that minimum of 7 days of moist curing is essential for concreting in hot climates.

2.3.2 Water cement ratio

Duff A Abram's water/cement ratio law, which states that fundamentally the strength of concrete is governed by the ratio of the weight of water to the weight of cement in a mix provided that it is plastic and workable, fully compacted and adequately cured (Taylor, 1977).

To eliminate excessive porosity, a minimum amount of water should be used. The volume of the products of hydration is nearly twice that of unhydrated cement (Powers, 1958). At water / cement ratio grater than 0.38, even if 100% hydration to occur, the products of hydration can not fill the entire volume of water filled spaces. The obvious conclusion is that the higher the water / cement ratio, the higher the porosity and the lower the strength (Jayathilaka, 1995).

However, the accurate measurement of water / cement ratio on site is difficult, due partly to variations in the moisture content of aggregates, partly to an inability to measure the quantity of water in fresh concrete under most practical conditions. However, for a given maximum size and type of aggregate and a given workability of concrete, the quantity of water per unit volume of compacted concrete is reasonably constant over a wide range of cement contents. Therefore, it is reasonable, in practice, to ensure that the cement content used exceed a particular minimum value which has been determined in such a way that the maximum water cement ratio is unlikely to exceed the value which it has been found necessary, from consideration of permeability and past experience (Shacklock, 1974).

There is a very significant influence of curing on sorptivity but that its effect on strength is minimal especially if the size of concrete elements are around 150 mm or greater (Dias, 1994).

Given that sorptivity is a measures of the quality of cover zone concrete and the fact that this zone plays a crucial barrier function in concrete durability ie in the protection of concrete (especially reinforced concrete) over time it is possible to say that curing is very important for durability (Dias, 1994).

Ben – Bassat et al, in 1990 have shown that w/c ratio and curing significantly affect the depth of carbonation, drying shrinkage, initial surface absorption, total absorption and oxygen permeability. However, the importance of curing was reduced as the water / cement ratio decreased.

Ho and Lewis (1988) showed that water / cement ratio is the decisive parameter governing carbonation depth, as opposed to water binder ratio, where blended cements are concerned.

2.3.4 Compaction of concrete

The aim of the concreting process is to achieve a homogeneous mass free from voids, and the planner must ensure that the concrete mix and compaction method are selected giving due consideration to the placing condition. (Masteron et al. , 1997)

1. Compaction of concrete shall not
    - be too short so that the concrete is not dense enough
    - be too long so that segregation takes place
    - result in a loss of entrained air
    - cause the gathering of water or air at certain location
    - leave any void
    - damage the formwork or change the position of reinforcing bars

2. Appropriate compaction energy imposed on the concrete shall be specified in terms of compaction time, compaction spacing and power of the compaction apparatus.

Chandrakeerthy et al. (1986) has recommended that the concrete should be compacted with either immersion or shutter vibrators. Compaction is very important for concrete with a slump of 10 – 15mm, while it is of a lesser importance for a concrete with a slump of 125 – 150mm.

The difference in strength between specimens subjected to 'high' and 'incomplete' compaction has also been found by Chandrakeerthy et al, (1986). For 1:2:4 concrete, the properly vibrated concrete yielded a mean equivalent cube strength of 21.6 N/mm^2 and incompletely vibrated concrete one of 13.9 N/mm^2. This is also confirmed by Dias in 1994. However, the effect of compaction on sorptivity is negligible (Dias, 1994).

2.4 Silica fume

2.4.1 General

Microsilica consisting of more than 90% of amorphous Silicon Dioxide has a quite high pozzolanic potential. This was first tested in 1947 in Norway and the large scale production was started in 1970s. The present use of concrete containing microsilica is over 5 milion m^3/year (Lewis, 2001). The term generally used for Microsilica in the concrete industry is silica fume. Microsilica concrete has been used in major projects either to produce high strength concrete or when enhanced durability was required (Lewis and Hasbi, 2001). Microsilica concrete has proved particularly beneficial in areas where the structures are subjected to severe environmental attack such as due to hazardous ground condition (Sulphate and Chloride attack), moisture exposure or physical degradation such as abrasion and erosion (Keck, 2001). The countries extensively use silica fume include United States of America, United Kingdom, countries in the Middle East, Hong Kong, Norway, Sweden, Denmark etc. Recently, India also started using silica fume in many large construction projects upon the realization of the advantages that silica fume could offer with enhanced durability.

2.4.2 The function and benefits of silica fumes

Silica fume is amorphous silicon dioxide. It is quite similar to silica dust (ground SiO_2), but only in appearance. When available in concrete, silica fume will combine with calcium hydroxide that is released by the hydration of cement, and produce more calcium silicate hydrates. This is the pozzlanic reaction that gives higher strength and impermeability. Due to the lack of free $Ca(OH)_2$, it could improve the abrasion resistance in both wet and dry conditions. Silica fume is a much finer material than cement particles. Therefore, it can spread well into the mix and hence enhance the cohesive nature of concrete thus improving workability while reducing the segregation and bleeding. Since silica fumes are very fine spherical particles, those can act as a lubricant to enhance the pumpability of concrete (Lewis et al; 2001).

Since silica fume could enhance both durability and strength, it has been used in many large scale projects in the world. Few of these are given in Table 1 obtained from Lewis and Hasbi(2001), Joshi(2001) and Saini et al.(2001).

Country	Project	Description	Reasons for using silica fumes
USA	311, South Wacker, Chicago, 70 storey 293 m high skyscraper in 1990	Silica fume concrete of 80 MPa was used with very low water contents such as 160 kg/m^3.	To achieve high strength and also to enhance the pumpability
USA	US Borax California, the slabs were subjected to chemical spillage containing 5% sulphuric acid in1986	50 MPa concrete was produced with 10% silica fumes.	To improve the durability quite significantly and also to reduce resistance to sulphate attack
USA	Kinzna dam, Pennsylvania in 1983	86 MPa concrete with 15% silica fumes	To improve the resistance to wet abrasion. The erosion was reduced by 40 times of normal concrete.
United Kingdom	Mayer Parry scrap metal reprocessing unit in 1992	80 MPa concrete with 10% silica fumes	To improve the resistance to dry abrasion. The erosion was reduced by 15 times of normal concrete.
Norway	Gullfaks off shore platforms	Grade 65 and 70 concrete was produced with 2% silica fumes.	To improve the workability and pumpability of concrete.

Abu Dhabi	Baynnuah Tower (building) of 156 in height in1992.	80 Mpa concrete with 10% silica fumes	To improve the durability and Chloride, Sulphate resistance in harsh environment of the Gulf region.
Hong Kong	Tsing Ma bridge, a suspension bridge with 200m tall towers and 2,167m length.	High strength concrete with 25% flyash and 5% silica fumes	To produce high strength concrete to suit stringent and comprehensive performance criteria.
India	Bandra – Worli sea link of length 5.86Km.	60 MPa concrete with 10% silica fumes	To reduce shrinkage cracking associated with high cement content and also to improve durability.
India	Viaduct in Mumbai.	75 MPa concrete with 10% silica fumes.	To ensure long term durability of the structure. This concrete has also given an excellent finish for the insitu and precast products.

Table 2.1: Application of concrete containing silica fume in many parts of the world

The details given in Table 1 indicate that silica fume has been used for both durability and high strength. Generally, silica fumes are added as an additional cementitious material as a percentage of the original cement content. When the silica fume content is 10%, it means that the weight of silica fume will be 40 kg/m^3 in a concrete containing 400 kg of cement per m^3. The details given in Table 1 indicates that in the above projects, silica fume were used from 2%-10% by weight. The guidelines given in Table 2 are suggested by Lewis (2001) for the use of silica fume.

Application	Percentage of silica fume by weight of cement
Pumping aid	2-3
Improved quality	4-7
Strength	7-15
Under water construction	12-15
Sprayed concrete	8-12

Table 2.2: The contents of silica fumes suggested for different applications

It was shown by Keck (2001) that about 7.5% silica fume by weight could reduce the chloride permeability by about 95% and could be used in the marine structures quite effectively. Silica fume (5% by cement weight) was used for reducing the drying shrinkage of bridge deck concrete in USA (Ramey & Cope, 2001). In Norway, 5% silica fume concrete was used to ensure good compaction of concrete, high chloride resistance and high strength (Fidjestol, 1993). Silica fume was found to be an excellent material to reduce the rebound of shotcrete in addition to improved durability. The silica fume content was about 8 % (Fidjestol, 1993)

Although silica fume has all these advantages, it is suggested by Neville (2001) that if it is intended to be used in a project, it should be clearly specified in the specification whether it is permitted and if permitted, where and how to use it. This is because, it is generally considered as a costly material and hence the benefits should outweigh the extra cost (Neville, 2001).

2.5 Durability

During the third quarter of the last century, a tremendous boom in construction activities occurred in the Western World, pushing the development of building materials and construction technology. Research and development were mainly geared towards optimization of load design and load bearing capacity, and did not take into account that at least some of these developments had negative effect on robustness, sensitivity to bad execution and duration of concrete structures (eg: pure strength oriented development of cement properties, increase of permissible stress, minimization of dimensions, reductions of cover etc) (Shies et al; 1996).

Although the initial concern about the concrete properties was regarding strength, there is now much concern about concrete durability. Here, too, the principal worldwide focus regarding concrete durability is on the protection of embedded steel (which is present in most concrete) from corrosion, although there is also some attention given to the protection of concrete itself (from phenomena such as sulphate attack and alkali aggregate reactions).

A durable concrete is one that performs satisfactorily in the working environment during its anticipated service life. The materials and mix proportions specified and used should be such as to maintain its integrity and, if applicable, to protect embedded steel from corrosion.

To achieve this, it is necessary to consider many interrelated factors at various stages in the design and construction process. Thus, the cover to steel is considered at the structural design stage involving consideration of the environmental conditions. Characteristics influencing the durability include its permeability and resistance to the ingress of the potentially deleterious substances. There are 3 fluids principally relevant to durability which can enter concrete: water pure or carrying aggressive ions, carbon dioxide and oxygen. They can move through the concrete in different ways, but all transport depends primarily on the structure of the hydrated cement paste. Durability of concrete largely depends on the ease with which fluids, both liquids and gases, can enter into, and move through, the concrete; this is commonly referred to as permeability of concrete. Permeability refers to flow through a porous medium. Now, the movement of various fluids through concrete take place not only by flow through the porous system but also by diffusion and sorption, so that our concern in really with penetrability of concrete. Penetrability of concrete is governed by the constituents, their proportions and the procedure used in making the concrete. A suitably low permeability is achieved by having an adequate cement content, a sufficiently low free water cement ratio, by ensuring complete compaction of concrete and by sufficient hydration of the cement through proper curing method.

It is unfortunate that the concrete has to be reinforced with embedded metal when used to resist tension or flexural loading. It is the potential corrosion of this embedded metal that is the prime cause of the majority of the structural concrete deterioration that is now becoming evident. Indeed, it has been estimated that in 1998, the value of building and civil engineering repairs and maintenance carried out in the UK was of the order of £ 15 billion of this approximately £ 500 million per annum is spent on concrete repair (Mays, 1999).

With such vast sums of money involved, it is important that the construction industry recognizes the unwitting errors of the past and puts to good effort the lessons that have been learned for new construction.

2.5.1 Sorptivity testing of concrete

Durability however is a long term property. Hence, appropriate indices have to be chosen for characterizing it. One such index that is gaining increasing acceptability is sorptivity (Hail, 1989), especially since it is concerned with the surface areas of concrete which protect the steel reinforcement, and also because sorptivity testing reflects to a reasonable extent some of the process by which actual deterioration of concrete will take place on site.

Dias (1994) obtained the volumes of water (from measured masses) absorbed per unit surface area, after various durations up to 49 hours, by cylinders coated on their curved surface and absorbing water through one flat face. A linear relationship can be obtained when plotting volume absorbed per unit surface area against the square root of time. The slope of this line is defined as the sorptivity of the specimen. Although, sorptivity is sensitive to specimen preconditioning there is some evident that repeatability in sorptivity results can be obtained even if preconditioning, varies to some extent. (Dias, 1994). The durability of concrete is generally affected by the corrosion of reinforcement. Thus, the quality of concrete in the cover region is quite important to enhance the durability. It is generally accepted that the sorptivity of concrete could give a very good indication of the quality of concrete. Although, in general, permeability is taken as the indicator of a concrete's ability to transport water (or oxygen and carbon dioxide), more precisely there are two mechanisms controlling the uptake and transport of water. Permeability, which is a measure of the flow of water under pressure in a saturated porous medium, and sorptivity, which characterizes the materials ability to absorb and transmit water through it by capillary suction. Whilst permeability is an important parameter for water retaining structures, a more important parameter (which is directly related to durability) for above ground structures is sorptivity.

Hence, sorptivity may be more convenient index of durability than is air permeability. It has also being argued that sorptivity, being sensitive to changes in mix constituents and workmanship factors, is a good index of concrete quality in general (Dias, 1995).

2.6 Summary

In BS 8110: Part 1: 1985, the enhancement of durability was achieved by using higher strength concrete. In obtaining higher strength with adequate quality controlling measures, weigh batching of constituent materials should be adopted. With this it is possible to use design mixes since any cement to aggregate ratio is achievable with weigh batching.

In Sri Lanka, still volume batching is often used due to non availability of weigh batching equipments with many small scale contractors. One nominal mix that is often used is 1: 2: 4 cement, sand and 20mm coarse aggregates. However this may give only a strength of about 20N/mm^2. However the minimum grade recommended in BS 8110: Part1: 1985 is Grade 25.

The mix of 1:1.5:3 of cement sand and 20 mm coarse aggregates is also not often adopted since is considered as an expensive mix. Therefore, there is an urgent need to develop cost effective mixes that could be practically used for Grades 25 and 30 concretes. This could be considered as a short term solution until weigh batching could be adopted in majority of construction sites in Sri Lanka.

Durability of concrete was improved by using other product like silica fume in many other parts of the world. However, this is not used very much in Sri Lanka. Therefore, it is useful to determine the possibility of using silica fume with locally available aggregates.

Therefore, in this research study, the development of economical nominal concrete mixes and the use of silica fume for enhancing the durability and the concrete strength was determined.

Chapter 3

3.0 QUESTIONNAIRE SURVEY

3.1 General

In order to determine the extent to which volume batched concrete is used in Sri Lanka, a detailed questionnaire survey was carried out with the participation of 132 practicing engineers. These engineers included civil engineers who function as structural design engineers or involve in construction as site engineers, resident engineers etc. Some have practiced as consultants and project managers. They represented leading public and private sector organisations. The average years of experience of these engineers was eight years. The profile of engineers is given in Table 3.1.

Type of the organisation	Site/ Construction Engineer	Project Manager	Structural/Design Engineer	Consulting Engineer
Public	17	08	12	13
Private	17	15	08	09
Public & private	05	07	10	11

Table 3.1 A summary of engineers surveyed

3.2 General information on questionnaire survey

A sample questionnaire survey form is given in Appendix A. The questionnaire was structured so as to encourage practising engineers to participate in the study and also help participants to provide the necessary information easily. The first part of the questionnaire contained the questions seeking information on the type of the work performed. For the convenience of the data processing, sites were categorized as small scale, medium scale and large scale whereas the construction type ranged from low and high rise buildings, bridge construction and irrigation work etc. The second part of the questionnaire was to find out the information on the type of concrete used whether it is ready mix, mix design or nominal mix (volume batching). The participants were given freedom to select more than one answer. The remaining part of the questionnaire was to find out the information about the volume batching in depth. They included the reasons to adopt volume batching, where it was used in a concrete structure and whether volume batching was used to obtain strengths such as Grades 25 or 30. It also examined whether extra cement was added to nominal mixes and the reasons for that. It further examined whether the corrective measures were taken to prevent bulking of sand.

3.3 The results of the questionnaire survey

The Chart 3.1 shows the percentage of the respondents involving with small scale, medium scale and large scale sites respectively.

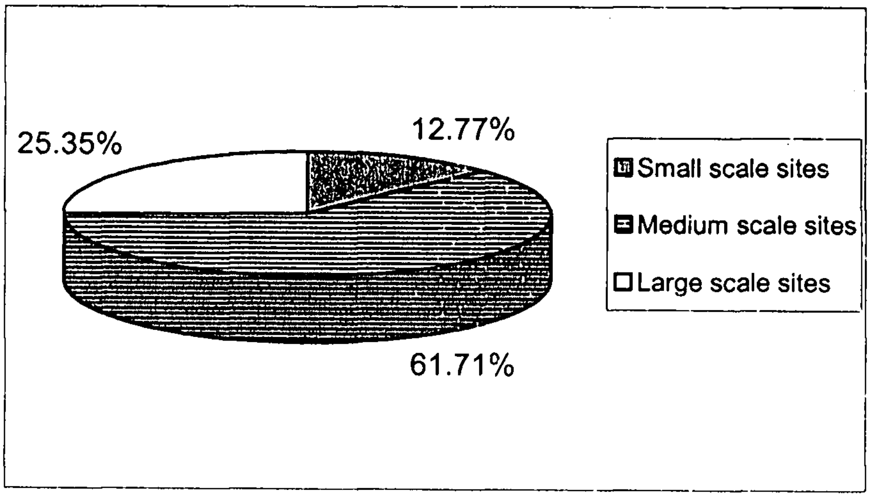

Chart 3.1 Percentage of the respondents involving with different scale sites

The table 3.2 shows the type of construction that the responders are involving with.

Type of construction	Number	As a percentage (%)
Building up to 3 stories	36	26.09
Building more than 3 stories	57	41.30
Bridges	27	19.57
Irrigation construction	03	2.17
Any other construction	09	6.82

Table 3.2 Number of responders involving with different type of construction.

Among the responders, most of them (67.39%) were involved with building sites. It is interesting to note that 45% of the responders generally used ready mix concrete whereas 45% of the responders usually used volume batching (Nominal mixes). The percentage using mix design in the site level was 10%. The results are shown graphically as follows. (Chart 3.2)

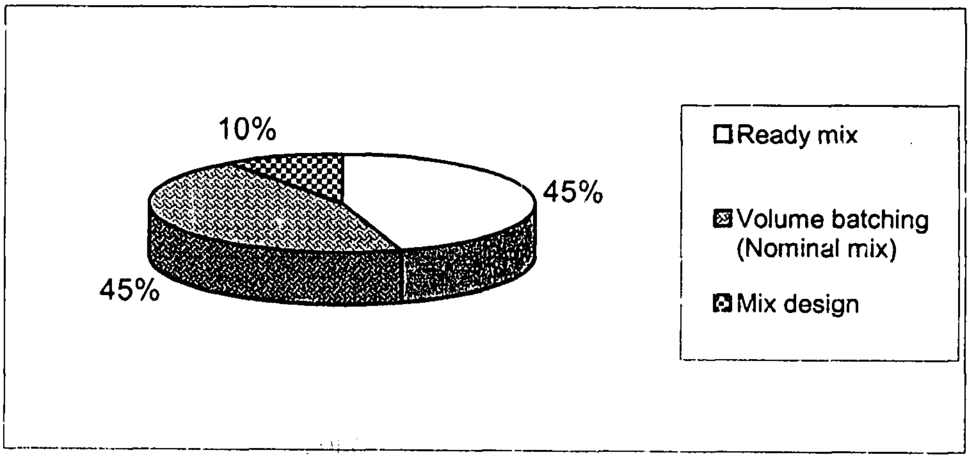

Chart 3.2 The concrete usage in the Sri Lankan construction industry

There were many reasons for the use of volume batching. Volume batching was selected by 61.36% due to its practicability and easy adoption at sites. This is the reason given by many engineers who were doing construction in rural areas except those involved with many large construction. Many other engineers (20.45%) used volume batching since it is the traditionally used method. Some others gave both the above reasons. Even in large construction sites, volume batching was used when small quantity of concrete was required. In fact, the sites around Colombo tend to use ready mix concrete for most of their sites. However, they also use volume batching, for small scale construction. 10% of those who are using ready mix concrete use volume batching to achieve demand for small quantity of concrete. The percentage using weigh batching to achieve the demand for small quantity of concrete is 2%.

The survey revealed that other than above explained reasons, there are some other factors volume batching to be used in the sites which are common irrespective of site location. One of the reason may be less specification given in the contract documents and hence the contractors have the freedom of choosing as their wish. The other reason may be that the volume batching may be ideal for concreting small quantities in different locations.

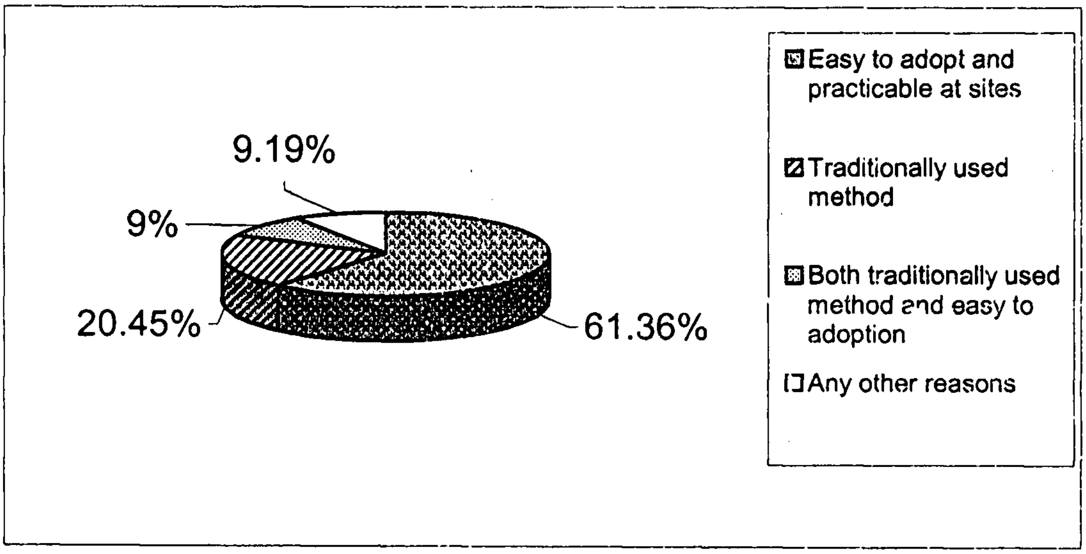

Chart 3.3 The reasons for the usage of the volume batching

The chart 3.4 shows the structural elements where volume bathed concrete was used.

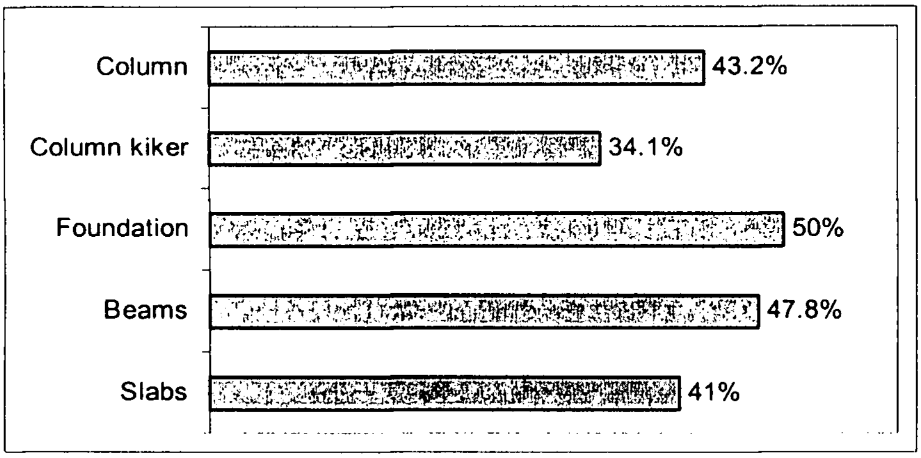

Chart 3.4 Percentage of responders using volume batching to produce different types of structural elements.

The result of the above chart shows that generally volume batched nominal mixes are used irrespective of the type of structural element.

Most of the cases, volume batched nominal mixes are used to produce Grade 20 concrete. However, in few circumstance, it is used to get even higher strength such as Grade 25 or 30. (Chart 3.5)

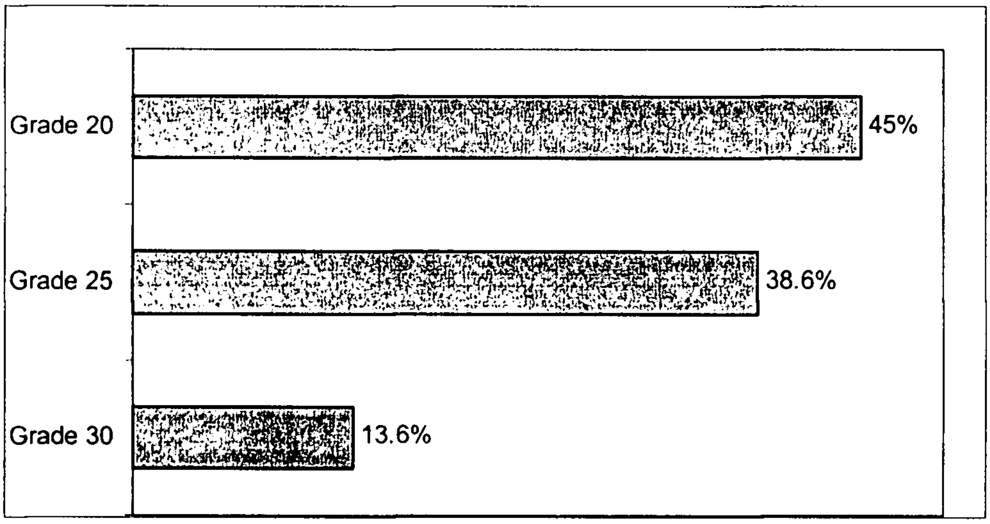

Chart 3.5 Percentage of responders using volume batching to produce different grades

It was found that 62.7% of those who are using volume batching tend to add additional cement to the volume batched concrete in special circumstances. This may be sometimes to increase strength, reduce segregation and bleeding as well as to increase workability. The reasons and the relevant percentages are shown in Chart 3.6.

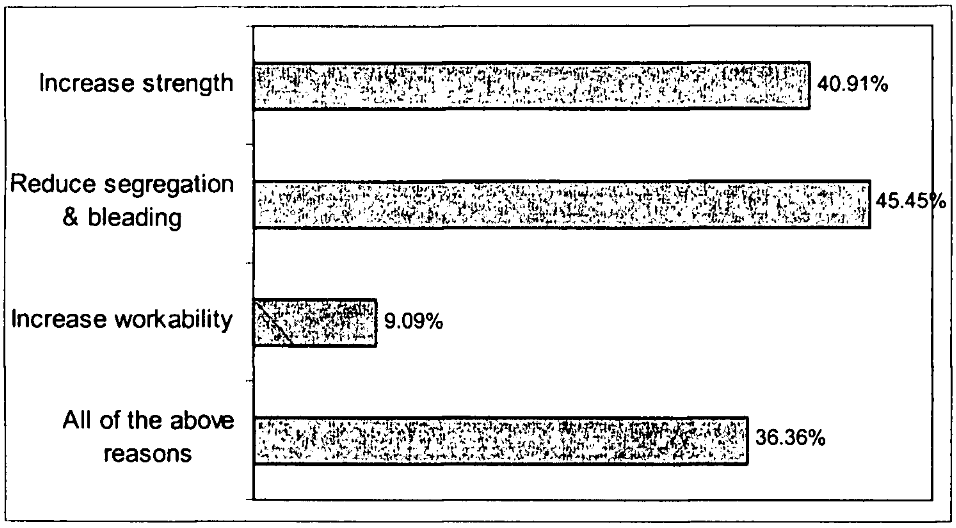

Chart 3.6 Reasons for the addition of additional cement

In volume batching, bulking of sand causes lot of quality shortfall. However, the survey revealed that 45.16% of those who are using volume batching do not consider it seriously. Only 54.84% took precautions to prevent bulking. 25.81% of volume batched users said that they keep sand away from rainwater to prevent bulking. 29.03% of volume batched users said that they account for reduction of sand volume (Chart 3.7).

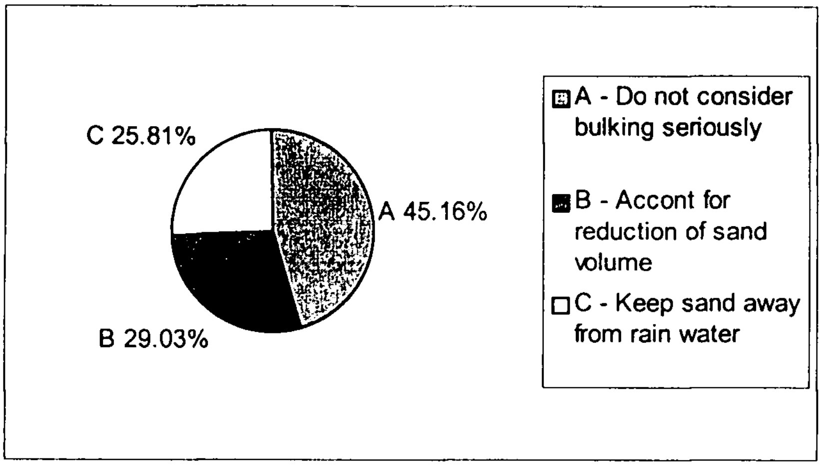

Chart 3.7 Responses for the bulking of sand.

It is interesting to note that if set of guidelines are prepared for the quality improvement of volume batched concrete, almost all the responders are willing to accept it. The results are shown in Table 3.3.

Response	Number	As a percentage(100%)
Yes	117	88.64
May be	15	11.36
No	0	0

Table 3.3: The number of responders agreeing with quality improvement of volume batching.

3.3 Summary

A questionnaire survey conducted among 132 practicing engineers yielded the following information:

1. It is found that 45 % of the responders generally used ready mix concrete whereas 45% of the responders usually used volume batching (Nominal mixes).
2. Its practicability and easy to adoption at sites are the reasons given by most of the volume batched users (61.36%).
3. Most of the time, volume batched mixes are used to produce Grade 20 concrete, however in few circumstances it is used to get even higher grades such as Grade 25 or 30.
4. Due to many different reasons, 62.7% of those who are using volume batching tend to add additional cement to the volume batched concrete.
5. Only 54.84% of those who are using volume batching took precautions to prevent bulking.
6. Most of the engineers are willing to adopt mixes that could give enhance strength economically.

Chapter 4

4.0 DEVELOPMENT OF ECONOMICAL VOLUME BATCHED CONCRETE MIXES FOR GRADES 25 &30 CONCRETES

4.1 General

In BS 8110 : Part1 : 1985, the improved durability of concrete was achieved by using mixes with higher strength such as grades 25 and 30. However, volume batched nominal mix of 1:2:4 (20 mm) is still used in many construction sites in Sri Lanka. This could be an undesirable situation which should be corrected with both short term and long term solutions. In this chapter, a cost effective short term solution is suggested to obtain grades 25 and 30 concretes based on a detailed experimental programme.

4.2 The objectives and the methodology

The main objective of the study presented in this chapter is to develop economical volume batched concrete mixes that could be used to obtain grade 25 and 30 concretes.

In order to achieve the above objective, the following methodology was adopted.

1. The possibility of improving the compressive strength of concrete by changing the cement content was investigated experimentally.

2. A detailed cost study was carried out to determine the cost increments associated with the proposed mixes when compared with 1:2:4 volume batched concrete. The cost saving relative to the currently recommended grade 25 and 30 mixes were also determined.

4.3 The experimental investigation

The coarse and fine aggregate used in Sri Lanka has a bulk density of about 1500-1600 kg/m^3. The solid density is about 2600-2700 kg/m^3. The water cement ratio used with 1:2:4 (20mm) volume batched concrete is about 0.55. Thus, it is possible to convert the 1:2:4 (20mm) volume batched proportion to weigh batched ratios with reasonable values for densities. This exercise was carried out with bulk densities of 1400 kg/m^3, 1550 kg/m^3, 1500 kg/m^3 for cement, sand and 20 mm aggregates respectively. The values used for solid densities were 3150 kg/m^3, 2650 kg/m^3 and 2600 kg/m^3, respectively (Shacklock, 1974). This indicates that the cement content per m^3 of concrete is about 310 kg/m^3 with 1:2:4 (20mm) volume batched concrete. This is well above the minimum cement content specified in BS 8110 : Part 1 : 1985.

A similar calculation for 1:1.5:3 (20mm) concrete indicates a cement content of about 375 kg/m^3. The cement content for 1:1:2 (20 mm) mix is about 485 kg/m^3. This indicates a quite high usage of cement associated with the mixes recommended for grade 25 and 30 volume batched concretes. Therefore, it is prudent to develop alternative mixes that achieves the required strength with lesser amount of cement.

When alternative mixes are suggested, it is essential to make them practically adoptable. One of the key features of all volume batched concrete is that the ratio between the coarse and fine aggregates was maintained as 2. This is for the practical purposes so that the same batching boxes could be used for fine and coarse aggregates. The extra strength of such mixes were then obtained by changing the cement content. However, the increase in cement content appears to be quite high.

It was reported by Shacklock (1974) that with a given set of materials and water cement ratio, the strength of concrete tends to increase as the aggregate to cement ratio decreases. Thus, increasing the cement content could be considered as a strategy for increasing the concrete strength. Therefore, in the present study the attention was placed to obtain an increase in strength by increasing the cement content by a lesser degree. For example, the cement content was increased by 10%, 20%, 30%. Such an increase in cement content is practically possible at sites since it is possible to make an extra gauge box of 10%, 20%, 30% the volume depending on the grade of concrete required.

4.3.1 The concrete mixes used for the study

The mix proportions used for the study are given in Table 4.1. It can be seen that only the cement content is increased as a percentage of the volume.

Identification	Mix proportion	% increase in cement
Mix No: 1	1:2:4	-
Mix No: 2	1.1:2:4	10%
Mix No: 3	1.2:2:4	20%
Mix No: 4	1.3:2:4	30%

Table 4.1: The concrete mixes used for the study

4.3.2 The method used for concrete cubes

For all the mix proportions, it was decided to ensure the workability remain the same. For most of the tasks where volume batching is used, a workability indicated by a slump of 50 – 60 mm would be sufficient. Since the water cement ratio that gives such a slump is not known, it is achieved in the following manner.

The constituent materials were initially fed to a tilting drum mixer with a water cement ratio of 0.4. After proper mixing, the slump is measured. At this water cement ratio, the mix generally had almost zero slump. Then water was gradually sprinkled and then mixed to improve the workability. The slump was measured at suitable intervals. As soon as the slump reached 50-60 mm, the mix was used to cast concrete cubes. A 50 mm to 60 mm slump is reasonable enough for most of the concreting purposes with adequate vibration (Schacklock, 1974). The additional quantity of water added was used to calculate the water cement ratio.

From each mix, nine cubes were made. The cubes were also made using the standard method. The cube was filled in three layers. Each layer was given 35 blows with a 1.8 kg hammer. These were tested at the ages of 7 days, 28 days, and 60 days. Because of the time limitation, instead of doing 90 days compressive strength testing, 60 days test was done. The cubes were demoulded one day after casting. All the cubes were kept in a water bath until the testing, after demoulding.

In order to ensure that comparison of results would be acceptable, the following controls were used for all the cubes.

1. Same brand of cement was used for a given batch
2. The coarse and fine aggregates were the same (Coarse aggregate is well graded nominal size of 20mm to 5mm and fine aggregate is well graded medium type of aggregate according to BS 882: 1983. The detailed results can be found in Appendix B)
3. The same mixing method was used for all the cubes
4. The same experimental programme was repeated with the other brands of cement

4.4 Results of the experimental study

The results of the experimental programme are shown below with four brands of cements for the mixes given in Table 4.2 and 4.3. The detailed results can be found in Appendix C

	Water cement ratio			
Mix	Brand 1	Brand 2	Brand 3	Brand 4
Mix 1 (1:2:4)	0. 54	0. 57	0. 55	0. 57
Mix 2 (1.1:2:4)	0. 51	0. 56	0. 54	0. 55
Mix 3 (1.2:2:4)	0. 50	0. 54	0. 53	0. 53
Mix 4 (1.3:2:4)	0. 43	0. 53	0. 52	0. 51

Table 4.2: The water cement ratios for a constant workability (slump value of 50-60mm) for different brands of cements

Mix	Average compressive strength in N/mm^2											
	Brand 1			Brand 2			Brand 3			Brand 4		
	7 days	28 days	60 days	7 days	28 days	60 days	7 days	28 days	60 days	7 days	28 days	60 days
Mix1	20. 5	28. 9	32.0	19. 5	27. 7	29. 5	20. 1	28. 7	31. 7	18. 5	26. 1	29. 2
Mix2	24. 8	33. 8	37. 2	23. 6	32. 1	35. 3	24. 6	33. 6	37. 5	23. 5	32. 2	35. 2
Mix3	27. 0	37. 0	38. 7	25. 2	36. 2	39. 1	28. 5	38. 2	40. 2	26. 3	36. 2	38. 1
Mix4	29. 7	40. 9	41. 4	27. 2	38. 0	42. 1	30. 1	42. 1	43. 1	28. 1	38. 7	40. 7

Table 4.3: The average compressive strength of concrete at 7 days, 28 days and 60 days for different brands of cements

Mix	The average compressive strength for all cements in N/mm^2		
	7 days	28 days	60 days
Mix 1 (1:2:4)	19. 6	27. 8	30. 6
Mix 2 (1.1:2:4)	24. 1	32. 9	36. 3
Mix 3 (1.2:2:4)	26. 8	36. 9	39. 0
Mix 4 (1.3:2:4)	28. 8	39. 9	41. 7

Table 4.4: The average compressive strength at 7 days, 28 days and 60 days

Four brands of popular cements were used as there could be variations in the cement properties from brand to brand. Under normal conditions adopted in Sri Lanka, a standard deviation of about 8 is usually used for concrete mixes. This gives a current margin of about 13 N/mm^2. This means, when Grade 20 concrete is needed, under laboratory conditions, a strength of about 33 N/mm^2 should be obtained as the mean strength.

However, it is stated that this current margin could be reduced by about 3.5 N/mm^2 when nine cubes were tested (Barnbrook et el.(1975)). Thus, the current margin required for the results given in Table 4.4 could be considered as 10 N/mm^2 since those are the averages values obtained for 12 cubes.

The results in Table 4.4 indicates that the use of Mix No: 3, which has 20% extra cement, could give a current margin in excess of 10 N/mm^2 for Grade 25 concrete at 28 days. Thus, Mix No: 3 could be sufficient for Grade 25 concrete. Similarly, Mix No: 4 could be recommended for Grade 30 concrete. It should be noted that these two mixes have given higher current margin than that obtained for 1:2:4 (20mm) nominal mix. It has given only about 7. 8 N/mm^2 for Grade 20 concrete.

It should be noted that all these results were obtained with strictly controlled constant workability (A slump value of 50 - 60 mm). However, at site conditions, it is difficult to expect such strictly controlled situations. Therefore, it is prudent to check the strength with higher slump values such as those giving collapse. Therefore, another set of experiments were carried out by increasing the slump until collapse only with Brands 3 and 4. The results of these experiments are in Table 4.5.

	Average compressive strength in N/mm^2 for almost collapse slump					
Mix	Brand 3		Brand 4		Average	
	28 days	60 days	28 days	60 days	28 days	60 days
Mix 1 (1:2:4)	19. 7	21. 4	23. 0	23. 7	21. 4	22. 6
Mix 2 (1.1:2:4)	24. 2	25. 7	24. 7	26. 2	24. 4	26.0
Mix 3 (1.2:2:4)	28. 4	32. 8	29. 1	32. 4	28. 8	32. 6
Mix 4 (1.3:2:4)	31. 7	33. 3	33. 2	33. 6	32. 5	33. 4

Table 4.5: The average compressive strength of concrete at 28 days and 60 days for very high workability (Almost collapse slump)

Even with collapse slump, Mix No:3, which has 20% extra cement has given a strength of 28.8 N/mm^2. Mix No: 4 has given a strength of 32.5 N/mm^2. The water cement ratio for these mixes were above 0.7. This indicates that even under adverse conditions, these mixes could give a sufficient strength.

4.5 The cost study

Since the same mix is used with additional cement such as 10%, 20%, and 30%, the extra cost would be primarily due to the cost of cement. The all the other costs such as aggregates, water and labour would remain approximately the same.

For these mixes, the cement content was calculated by using the bulk and solid densities given in Section 3. These values are given in Table 4.6 with the likely extra cost per m^3 of concrete. The price of a 50 kg bag of cement was considered as Rs 370/=. The detailed calculations are given in Appendix D.

Mix	Cement content (kg)	Increase of cement (kg)	Extra cost Rs.(With respect to the cement)
Mix 1 (1:2:4)	310		
Mix 2 (1.1:2:4)	325	15	110/=
Mix 3 (1.2:2:4) Proposed Grade 25	350	40	295/=
Mix 4 (1.3:2:4) Proposed Grade 30	380	70	520/=

Table 4.6: The table showing cement content, increase in cement content and the extra cost for different concrete mixes proposed.

Mix	Cement content (kg)	Increase of cement (kg)	Extra cost Rs.	Cost savings (with respect to cement) with proposed mix per m^3
Grade 20 (1:2:4)	310	-	-	-
Grade 25 (1:1.5:3)	375	65	480/=	185/=
Grade 30 (1:1:2)	485	175	1295/=	775/=

Table 4.7: The Table showing cement content, increase of cement content and extra cost for the existing concrete mixes.

The comparison of Tables 4.6 and 4.7 indicates the likely cost increase for Grades 25 and 30 concretes with the proposed mix and those generally recommended. This clearly shows that there is a very good potential to adopt the proposed mixes immediately as a short term solution to improve the strength of concrete used in Sri Lankan construction industry. This would be extremely useful in many remote sites where it is not possible to obtain ready mix concrete. If bulking is considered, the existing Grade 20, Grade 25 and Grade 30 concrete require cement content of 360 kg, 435 kg and 560 kg per m^3 of concrete, respectively. The minimum cement content according to ICTAD specification (1988) for Grade 20, 25 and 30 respectively are 320 kg, 405 kg and 552 kg per m^3 of concrete, respectively.

However, when these volume batched concrete is used for higher strength concrete, the following precautions could be suggested based on the past research carried out in Sri Lanka:

1. The strength of concrete could be affected by the compaction effort. It is proposed by Chandrakeerthy et al. (1986) that the concrete should be compacted with either immersion or shutter vibrators. This suggestion should be applied for the proposed mixes since hand compaction could give much variability in strength due to poor compaction.

2. The strength of concrete and also the workability could be improved with well graded aggregates. Therefore, blending of 20 mm aggregates with small aggregates was recommended by Chandrakeerthy (1987). This could be achieved generally by blending 20 mm aggregates with 8 mm chips with a ratio of about 3:1.

3. The water cement ratio affects strength and durability as described by Dias (1994) with detailed experimental programme carried out using sorptvity of concrete. Therefore, the control of slump to the required level with slump cone test at the site will be quite useful as recommended by Chandrakeerthy (1987) with volume batched concrete. This will allow to vary the water content depending on the variation of moisture content in the aggregates such as that occur in rainy days.

4. It is advisable to select a suitable mixing time depending on the concrete mixer available at the site so that a concrete mix of uniform colour could be obtained. It was reported by Chandrakeerthy (1987) that improper mixing of concrete could create many problems such as low workability and honeycombs.

5. As reported by Dias (1994) that curing of concrete could affect the durability of concrete very much under Sri Lankan conditions. Therefore, adequate curing of concrete also should be given sufficient attention. It was reported by Chandrakeerthy (1987) that the volume batched concrete made under careful control at the site could reduce the variability of strength.

Therefore, it could be suggested that the volume batched concrete mixes suggested based on this experimental study should be used with extra quality control measures identified by the past research work.

4.6 Summary

It is shown that volume batched Grade 20 concrete has been used at many construction sites in Sri Lanka, although BS 8110: Part 1: 1985 recommends higher grades. Therefore, it is useful to develop cost effective nominal mixes that could be adopted at least short term. It is shown that the nominal mixes presently adopted in Sri Lanka for Grades 25 and 30 concretes use quite high amount of cement and could be considered as expensive for many projects. These values are approximately 375 kg/m^3 and 485 kg/m^3.

The detailed experimental programme carried out has revealed the following:

1. It is possible to use 1:2:4 (20 mm) volume batched concrete with 20% and 30% extra cement to obtain Grade 25 and 30 concretes, respectively.

2. It is prudent to use a reasonable quantity of water so that the slump will remain in 50 to 60 mm range. However, even with higher water cement ratios also, the above mixes gave sufficient strength.

3. The approximate cement content in the proposed mixes for Grade 25 and 30 are 350 kg/m^3 and 380 kg/m^3, respectively. However, the cement content of the existing mixes for the Grades 25 and 30 concrete are 375 kg/m^3 and 485 kg/m^3, respectively. This indicates a saving of 25 kg/m^3 and 105 kg/m^3 of cement. Thus, there would be cost saving of about Rs 185/= per m^3 and Rs 775/= per m^3 of concrete.

4. The cement contents for Grades 20, 25, 30 could be approximately given as 310, 350 and 380 kg/m^3. Therefore, the proposed mixes will cost about Rs 295/= and Rs 520/= per m^3 than Grade 20 concrete. Since the cost of 1m^3 of Grade 20 concrete is about Rs 4500/=, these increases will be in the range of 6% and 11% for Grade 25 and 30 concretes, respectively. Since Grade 25 concrete is generally recommended in Sri Lanka, there is a very high possibility for adopting the proposed mix for Grade 25 at many construction sites. If higher Grade such as 30 is specified, the proposed mix with 30% extra cement could be used. When even higher grades are specified, it is advisable to use weigh batching since it would need grater quality control.

Chapter 5

5.0 EFFECT OF SILICA FUME ON STRENGTH AND DURABILITY

5.1 General

Silica fumes are used many parts of the world to improve the desirable qualities of concrete such as strength, impermeability, abrasion resistance and pumpability. However, it has not been used in Sri Lanka so far in a significant scale. Therefore, it is useful to investigate the effect of silica fume with commonly used aggregate in Sri Lanka. With a detailed experimental study, it was shown that 5% to 10% silica fume by the weight of cement could improve the strength while reducing the sorptivity. Thus, silica fume could be used in Sri Lanka to enhance the desirable properties of concrete with commonly used aggregate.

5.2 The main objectives and methodology

The main objectives of the research study are the following:

1. To determine the strength enhancement that can be achieved with the silica fumes for selected concrete mixes.
2. To assess the effect of silica fumes on the long term durability of concrete.
3. To determine the appropriate percentages of silica fumes to obtain the desirable strength and durability characteristics.

The following methodology was adopted to achieve the above objectives:

1. A comprehensive literature review was carried out to gather as much details as possible about the application of silica fumes in low and high strength concretes.

2. A detailed experimental programme was carried out to determine the effect of silica fumes on strength characteristics. The effect on durability was also determined for the same concrete by using the sorptivity testing.

3. The above results were used to recommend suitable percentages for silica fumes to be used with concrete, specially with low strength concretes in the context of improving durability.

5.3 The experimental programme

The experimental programme was aimed to find out the effect of silica fumes on the strength of concrete. For this purpose, the cube test results of a number of mixes were used at the ages of 7 days and 28 days.

5.3.1 The experimental programme for strength

The principal factors that affect the properties of concrete are the mix proportions (especially the cement content), the slump achieved (primarily depend on water content), compaction during placing and curing after casting. In order to isolate the effect of cement content and the silica fume percentage, the trial mixes given in Table 5.1 were selected. It was found that 20% and 30% extra cement by volume in 1:2:4 (20mm) volume batched concrete could give Grade 25 and 30 concretes, respectively. Therefore, for this study, volume batched concrete with these mixes was used although the facilities were available to produce weigh batched concrete.

Mix	Proportion	Approximate cement content kg/m^3
M_1	1:2:4 with 0% extra cement by volume	310
M_2	1:2:4 with 10% extra cement by volume	325
M_3	1:2:4 with 20% extra cement by volume	350
M_4	1:2:4 with 30% extra cement by volume	380

Table 5.1: The trial mixes used for the experimental programme and the approximate cement contents

For these mixes, the silica fume was used with 0%, 5% and 10%. These are identified as S_0, S_1 and S_2 respectively. The coarse aggregate used is well graded nominal size of 20mm to 5mm and fine aggregate is well graded medium type of aggregate according to BS

882:1983. The full details of the mixes used for the experimental programme are given in Table 5.2.

Identification	Mix propotion	Approximate Cement content per m^3	Silica fume content per m^3	% increase of cement volume relative to 1:2:4 mix	% increase of silica fume (by weight)
M_1S_0	1:2:4	310	-	-	-
M_1S_1	1:2:4+5% SF	310	15	-	5%
M_1S_2	1:2:4 + 10% SF	310	30	-	10%
M_2S_0	1.1:2:4	325	-	10%	-
M_2S_1	1.1:2:4 +5% SF	325	16	10%	5%
M_2S_2	1.1:2:4 +10% SF	325	32	10%	10%
M_3S_0	1.2:2:4	350	-	20%	-
M_3S_1	1.2:2:4 +5% SF	350	17.5	20%	5%
M_3S_2	1.2:2:4 +10% SF	350	35	20%	10%
M_4S_0	1.3:2:4	380	-	30%	-
M_4S_1	1.3:2:4+5% SF	380	19	30%	5%
M_4S_2	1.3:2:4+10% SF	380	38	30%	10%

Table 5.2: The concrete mixes used for the study

5.3.2 The method used for concrete cubes

For all the mix proportions, as it was decided to ensure that the workability remain the same. A workability indicated by a slump of 50-60 mm was selected as it is sufficient for most of the concreting processes. Since, the water cement ratio that gives such a slump is not known, it is achieved in the following manner. First the constituent materials were initially fed to a tilting drum mixer with a water cement ratio of 0.4. The slump was measured after proper mixing. At this water cement ratio, the mix generally had almost zero slump. Then, the water was gradually sprinkled and then mixed to improve the workability. The slump was measured at suitable intervals. As soon as the slump reached

50-60 mm, the mix was used to cast concrete cubes. The additional quantity of water added was used to calculate the water cement ratio.

From each mix, 6 cubes were made using the standard method. The specimens being compacted on a vibrating table in three layers (until air bubble ceased to appear at each layer) into 150 mm cube moulds. Demoulding was done on the day after casting. Curing was carried out until the compressive strength was determined.

5.3.3 The sorptivity testing procedure

The nine mixes given in Table 5.1 were used for this programme as well. The moulds used for this programme were specially fabricated for casting concrete cylinders of 100mm diameter x 100mm length PVC moulds. A 6mm thick Perspex plate was secured to one end and given a coat of formwork release agent between the plate and cylinder. The concrete cast against the Perspex surface was used as the working surface. Inside of the cylinders was applied with mould oil to ease the removal of cast specimens. From each mix, two specimens were compacted into the moulds in two layers so that it is having medium level of compaction which gives a more realistic representation of the site practice. The time for the medium level of compaction was obtained by vibrating the quarter of the duration employed for higher compaction as used by Dias (1994). The time required for such a high compaction was obtained when the air bubble had ceased to appear at each layer. The casted cylinders are shown in Figure 5.1.

The demoulding procedure employed were identical to that of cube case. Dias (1991) has recommended a minimum of 7 days of moist curing for concreting in hot climates. Hence, in order to match site conditions, the specimens were cured for 7 days. After the above curing, all the specimens were kept in an oven for 48 hours at constant temperature of 50 ^{0}C until the moisture equilibrium was achieved. (ie. the specimen stopped loosing mass). After mass stabilization, the specimens were coated with two layers of an epoxy resin on their curved surface only, in order to ensure uniaxial water absorption. They were made to absorb water with their axes vertical, through sponges of 12mm placed in a shallow tray of water. Sponges were saturated in water and water level inside the tray was controlled such that half the thickness of sponges to promote the water absorption. Cast surface of specimens were used for sorptivity testing, because most surface of site cast concrete would be cast as opposed to free. The specimens at the sorptivity testing are shown in Figures 5.2 and 5.3.

The masses of the specimens were then taken after 1, 4, 9, 25 and 49 hours of absorption. The determination of mass was done by removing the specimens from their sponges, shaking off excess moisture and placing them with their dry surface on an electronic pan balance, so that absorbing surface would not be touched, and then return them to their sponges. It was assumed that no disturbance to the absorption process occur as weighing operation was completed in under 15 seconds.

The sorptivity was obtained by plotting the volume absorbed per unit wetted area aginst the square root of time (in $hr^{0.5}$). The absorbed masses were converted to volumes assuming a density of 1000 kg/m^3 for water. The slopes of the above line yielded the sorptivity of the specimens (in $mm/hr^{0.5}$).

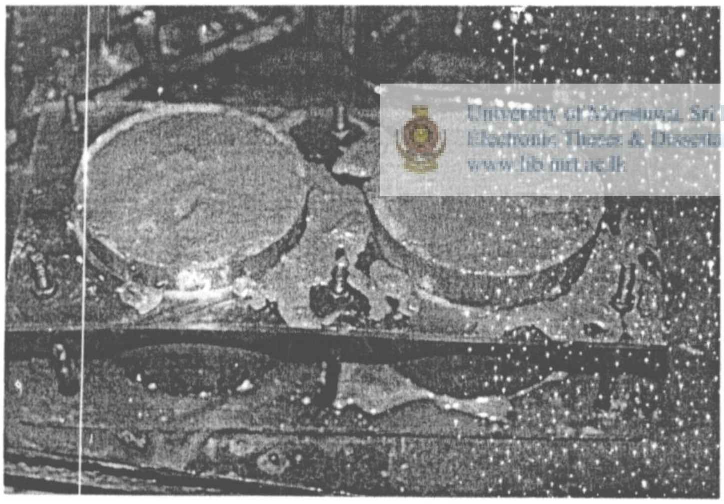

Figure 5.1: The casted cylinders for sorptivity testing

Figure 5.2: The sorptivity testing specimens

Figure 5.3: The sorptivity testing is in progress

5.4 The results of the experimental study

The water cement ratio is generally considered as the factor with dominant influence on workability and strength of concrete. This term is applicable only when cement and water is used. As soon as silica fume is used, it introduces an additional material that can contribute to the strength. Therefore, the term called water-binder ratio could be introduced. For a concrete with 325 kg of cement, and 16 kg of silica fume, the water cement ratio that gives 50-60mm slump is 0.45 (about 146 kg of water). The corresponding water to binder ratio is 0.43. This value is obtained by dividing the water content by total cementious material (i.e. cement + silica fume, 146/(325+16)).

Mix	Water cement ratio	Water binder ratio
M_1S_0	0.51	0.51
M_1S_1	0.50	0.48
M_1S_2	0.52	0.47
M_2S_0	0.49	0.49
M_2S_1	0.45	0.43
M_2S_2	0.46	0.42
M_3S_0	0.47	0.47
M_3S_1	0.44	0.42
M_3S_2	0.46	0.42
M_4S_0	0.44	0.44
M_4S_1	0.44	0.42
M_4S_2	0.47	0.43

Table 5.3: The water cement ratio and water binder ratios for a constant workability (Slump value of 50-70mm)

The water to cement (w/c) ratio and water to binder (w/b) ratio used for the experimental programme are given in Table 5.3. This table indicates that the use of silica fume has reduced the water to binder ratio in most of the mixes. This may support the fact that the presence of silica fume improves the workability

Under compressive loads, failure in normal concrete occurs either within the hydrated cement paste or along the interface between the cement paste and aggregate particles. This interface is a weak area in normal concrete. In order to improve the strength, it is necessary to strengthen this weak area. Reducing the water binder (w/b) ratio by using supplementary cementitious material like silica fume tends to strengthen the weaker zone. The calcium silicate hydrate produced as a result of the reaction between silica fume and $Ca(OH)_2$ produced as a result of hydration of cement could improve the strength and impermeability (Joshi, 2001).

The average strength recorded for slump between 50-70 mm for different mixes are given in Table 5.4. The detailed cube strength results with silica fume is given in Appendix E. The mixes M_3S_0 and M_4S_0 recommended for Grades 25 and 30 gave a current margin in excess of 13 N/mm^2 at 28 days.

Mix	7 days compressive strength in N/mm^2	Average 7 days compressive strength in N/mm^2	28 days compressive strength in N/mm^2	Average 28 days compressive strength in N/mm^2
M_1S_0	19.10 18.20 18.23	18.51	29.21 29.43 29.35	29.33
M_1S_1	22.58 22.30 22.5	22.46	33.71 33.52 33.57	33.60
M_1S_2	21.41 21.83 21.77	21.67	36.52 36.71 36.63	36.62

Mix	7 days compressive strength in N/mm^2	Average 7 days compressive strength in N/mm^2	28 days compressive strength in N/mm^2	Average 28 days compressive strength in N/mm^2
M_2S_0	22.78 22.53 22.85	22.72	35.81 35.43 35.56	35.60
M_2S_1	24.20 24.12 24.31	24.21	36.71 37.79 37.49	37.63
M_2S_2	23.21 22.98 23.11	23.10	36.82 37.24 37.24	37.10
M_3S_0	26.17 26.41 26.35	26.31	38.93 39.51 39.46	39.30
M_3S_1	30.10 29.21 29.04	29.45	46.21 45.84 45.74	45.93
M_3S_2	27.52 27.79 27.70	27.67	45.72 45.59 45.73	45.68
M_4S_0	27.84 27.90 28.17	27.97	47.61 47.72 47.59	47.64
M_4S_1	28.42 28.19 28.26	28.29	47.79 47.71 47.84	47.78
M_4S_2	28.17 28.32 28.14	28.21	47.49 47.61 47.58	47.56

Table 5.4 : The average compressive strength of concrete at 7 days and 28 days

These results indicate that 5% silica fumes could give strength enhancement for concrete mixes such as 1:2:4 (20mm) and 1:2:4 (20mm) with 10% and 20% more cement. This is consistent with the observations reported by the other researchers in literature. When 20 % and 30 % more cement were used, the silica fume did not give an enhancement of strength. This is not the expected result. It could be that the ratio of fine to coarse aggregate of 1:2 may not be working in this strength range. This should be investigated in future research. However, the results for M_4S_0 shows that the mix with 30% extra cement could be used for Grade 30 concrete with a lot of confidence. The current margin given is about 17.5 N/mm^2

The sorptvity test results are given in Table 5.5. The detailed sorptivity test results are given in Appendix F. These results indicate a significant reduction in sorptivity for all the mixes with extra cement and 5% and 10% of silica fume. For example, the sorptivity achieved by using 5% silica fumes with 20% extra cement is approximately equal to the sorptivity of concrete with 30% extra cement and no silica fume. Thus, the reduction in sorptvity that is achieved with extra cement could be achived by using about 5% silica fumes. Even a better reduction can be achieved with 10% silica fumes.

Specimen	Sorptvity (mm3/hr$^{0.5}$)	Sorptivity as a ratio of concrete with 0% silica fume
M_1S_0	1.037	1.00
M_1S_1	0.529	0.51
M_1S_2	0.528	0.51
M_2S_0	0.747	1.00
$M2S_1$	0.392	0.52
M_2S_2	0.250	0.33
M_3S_0	0.300	1.00
M_3S_1	0.244	0.81
M_3S_2	0.147	0.49
M_4S_0	0.229	1.00
M_4S_1	0.152	0.66
M_4S_2	0.098	0.43

Table 5.5: Sorptvity results of the mixes

Based on the results given in the Table 5.5, the following could be summarized:

1. When the cement content is increased in concrete as in M_1S_0, M_2S_0, M_3S_0 and M_4S_0, the sorptvity reduces. This means, the durability of concrete can be improved by increasing the cement content.

2. When cement content is low, 10% silica fume has not given much advantage. This may be that the amount of $Ca(OH)_2$ produced is not sufficient to react with all silica fume.

3. In all other mixes (M_2, M_3, M_4), 10% silica fume has given a lower sorptivity than 5% silica fume. The use of 5% silica fume has given a lower sorptivity than concrete without silica fume.

4. Therefore, it is reasonable to suggest that silica fume could be used in Sri Lanka even with low Grades of concrete such as 20 or 30 to improve the durability. This would be particularly useful in situation such as irrigation channels and factory buildings since silica fumes could improve the abrasion resistance under both wet and dry condition. It could also be used in highway bridges since the long term durability of concrete is often could be a problem in coastal roads.

It would also be possible to use silica fumes in buildings especially when the fair finish is given with the formwork without plastering. It is reported that the concrete containing silica fume could give much better finish due to improved workability and reduced bleeding and segregation. With these encouraging results, it is prudent to pursue further applications of silica fumes specially with respect to the ready mix concrete since it could enhance the pumpability in addition to the other benefits.

5.4 Summary

The strength and durability are important properties of concrete. The strength of concrete could be improved by using extra cement. It is shown with the experimental study that the sorptivity of concrete containing higher cement content will be lower. This means, the concretes containing higher cement contents could be used for enhanced durability.

Silica fume, when used with 5% by weight of cement, could enhance the strength of concrete. It could lower the sorptivity of concrete as well. When 10 % silica fume are used, the sorptvity could be lowered further. This means, with the fine and coarse aggregate used in Sri Lanka, silica fume could give higher strength with enhanced durability. This is an important finding. Thus, it will be useful to explore the benefits of using silica fume for ready mix concrete as well, either to achieve better quality wet or hardened concrete. This will need further detailed research since silica fume is expensive and hence benefits should be justified with respect to the cost.

Chapter 6

6.0 CONCLUTIONS AND FUTURE WORK

The main objectives of this study were to develop economical volume batched concrete mixes that could be confidently recommended for grades 25 and 30 concretes and to determine the effectiveness of silica fume with locally available aggregates.

A comprehensive literature review was conducted to determine the ways and means of improving the strength and durability of concrete. A questionnaire survey was conducted to assess the extend to which the volume batched concrete is used at the Sri Lankan construction industry. The possibility of improving the compressive strength of concrete by changing the cement content was investigated experimentally. A detailed cost study was carried out to determine the cost increments associated with the proposed mixes when compared with 1:2:4 volume batched concrete. The cost saving relative to the currently recommended grade 25 and 30 mixes were also determined. The possibility of improving the compressive strength and durability of concrete by the introduction of a small amount of silica fume was investigated experimentally. Sorptivity was used as the measure of durability. Based on this detailed study, a number of quite useful conclutions could be made, which would have many practical applications.

6.1 Conclusions and recommendations

1. The questionnaire survey revealed that about 45% of the site of Sri Lankan construction industry used volume batched concrete to attain its concrete demand. The use of volume batched concrete is very much significant in the outstation sites where ready mix concrete is not available.

2. Hence, in improving the quality of concrete, it is quite worth of concentrate on volume batched concrete.

3. Although, 1:2:4 nominal mix which gives Grade 20 concrete is quite popular, the mixes such as 1:1.5:3 and 1:1:2, which gives Grade 25 and 30, respectively, are not so popular due to the high cost. This might create an undesirable situation where designs carried out with grade 25 concrete could be constructed with 1:2:4 nominal mix concrete having lower characteristic strength and durability.

4. It is possible to use 1:2:4 (20 mm) volume batched concrete with 20% and 30% extra cement to obtain grade 25 and 30 concretes, respectively. Such an increase in cement content is practically possible at sites since it is possible to make an extra gauge box of 20% and 30% the volume depending on the grade of concrete required. It is prudent to use a reasonable quantity of water so that the slump will remain in 50 to 60 mm range. However, even with higher water cement ratios also, the above mixes gave sufficient strength.

5. Based on the past research carried out in Sri Lanka, when volume batching is used to attain higher grades, some precautions could be suggested. As proposed by Chandrakeerthy et al. (1986), the concrete should be compacted with either immersion or shutter vibrators. As suggested by Chandrakeerthy (1987), the strength and workability of concrete could be improved by blending of 20 mm aggregates with 8 mm chips with a ratio of about 3:1. Moreover, the control of slump to the required level with the slump cone test at the site will be quite useful which will allow to vary the water content depending on the variation of moisture content in the aggregates such as that occur in rainy days (Chandrakeerthy, 1987). As suggested by Dias (1994), at least 7 days of moist curing should be carried out for Sri Lankan conditions. In fact, it is advisable to select a suitable mixing time depending on the concrete mixer available at the site so that the concrete mix of uniform colour could be obtained.

6. The approximate cement content in the proposed mixes for grade 25 and 30 are 350 kg/m^3 and 380 kg/m^3, respectively. However, the cement content of the existing mixes for the grades 25 and 30 concrete are 375 kg/m^3 and 485 kg/m^3, respectively. This indicates a saving of 25 kg/m^3 and 105 kg/m^3 of cement. Thus, there would be cost saving of about Rs 185/= per m^3 and Rs 775/= per m^3 of concrete. The proposed mixes

will cost about Rs 295/= and Rs 520/= per m^3 than grade 20 concrete as the cement contents for grades 20, 25, 30 could be approximately given as 310, 350 and 380 kg/m^3. Since the cost of $1m^3$ of grade 20 concrete is about Rs 4500/=, these increases will be in the range of 6% and 11% for grade 25 and 30 concretes, respectively. Since grade 25 concrete is generally recommended in Sri Lanka, there is a very high possibility for adopting the proposed mix for grade 25 at many construction sites. If higher grade such as 30 is specified, the proposed mix with 30% extra cement could be used. It is advisable to use weigh batching when even higher grades are specified since it would need grater quality control.

7. Since the building industry in Sri Lanka is responsible for the over exploitation of many of its natural resources, it is important to suggest either alternative building materials or improve the life span of the new structures. The use of microsilica (silica fume) in concrete could have application in this area with the enhanced durability that it could offer for the concrete.

8. The results in Table 5.4 indicates that 5% silica fumes could give strength enhancement for concrete mixes such as 1:2:4 (20mm) and 1:2:4 (20mm) with 10% more cement. This is consistent with the observations reported by the other researchers in literature. When 20 % and 30 % more cement were used, the silica fume did not give an enhancement of strength which is not the expected result. It could be that the ratio of fine to coarse aggregate of 1:2 may not be working in this strength range. This should be investigated in future research.

9. The sorptivity test results given in Table 5.5 shows when the cement content is increased in concrete, sorptivity reduces hence improving the durability. When the cement content is low, 10% silica fume has not given much advantage on sorptivity, may be because of the amount of $Ca(OH)_2$ produced is not sufficient to react with silica fume. However, when the cement content is high, 10% silica fume has given a lower sorptivity than 5% silica fume. The use of 5% silica fume has given a lower sorptivity than concrete without silica fume. The sorptivity achieved by using 5% silica fumes with 20% extra cement is approximately equal to the sorptivity of concrete with 30%

extra cement and no silica fume. Thus, the reduction in sorptvity that is achieved with extra cement could be achived by using about 5% silica fumes. Even a better reduction can be achieved with 10% silica fumes.

10. Hence, even with low grades of concrete such as 20 or 30, addition of silica fume could be suggested to improve the durability. Since silica fume could improve the abration resistance under both wet and dry conditions, it would be particularly useful in situation such as irrigation channels and factory buildings. Silica fume also could be used in highway bridges since the long term durability of concrete is often a problem in coastal roads.

6.2 Future work

Due to constraints of time and manpower, this study could not cover certain aspects adequately. The following could be recommended for future work:

1. The experimental programme with silica fume should be extended to produce high strength concrete having higher durability. For this, different dosages of silica fume as well as available chemical admixtures could be used. Moreover, it is prudent to pursue further application of silica fume specially with respect to the ready mix concrete since it could enhance the pumpability in addition to the other benefits. As silica fume is a costly material, a cost benefit analysis should be carried out so that benefits should outweigh the extra cost.

2. The effect of silica fume on sorptivity should be investigated when admixtures are used. It will also be useful to determine the effect of silica fume and admixtures on the properties of green concrete such as the formation of plastic shrinkage cracking.

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Appendix A-Form of questionnaire survey

Questionnaire survey

Project: Development of nominal mixes suitable for small construction industry in Sri Lanka

Researchers: Dr M. T. R. Jayasinghe & Mr P. T. R. S. Sugathadasa

Funding: Asian Development Bank Funded S.T.P.D.P project of Ministry of Science and Technology

Name:

Address:

Post & current place of work:

No of years experience:

Underline your choice or tick where necessary. You may give more than one answer. (Multiple answers are possible)

1. What kind of site or project are you currently working in?
    1). Small Scale ☐
    2). Medium Scale ☐
    3). Large Scale ☐

2. What is the type of construction?
    1). Buildings up to 3 stories ☐
    2). Buildings more than 3 stories ☐
    3). Bridges ☐
    4). Irrigation construction ☐
    5). Any other (Please specify) ☐

3. Concrete types used
    1). Ready mix ☐ 3). Nominal mix (Volume batching) ☐
    2). Mix design ☐ 4). Combination of above 1 or 2 with 3 ☐

4. If volume batching is used, then the reason is
    1). It is easy to adopt ☐
    2). Traditionally used method ☐
    3). Both of the above method ☐
    4). Any other (Please specify) ☐

5. If you are working with volume batching, where do you use them?
   (Please tick where necessary & specify the mix as in the order of cement, sand, aggregate for each case) **cement:sand:aggregate**

   Columns ☐
   Column kiker ☐
   Foundations ☐
   Beams ☐
   Slabs ☐

6. Do you use volume batched concrete, when grade 25 or 30 concrete is needed?
   1). Yes ☐
   2). No ☐

7. If the answer is 'Yes' what mixes do you use?
   Cement:sand:aggregate
   Grade 25

   Grade 30

8. If you rely on ready mix concrete, how do you achieve the demand for small quantity of concrete?
   1). Nominal mixes (Volume batching) ☐
   2). Mix design ☐

9. Do you add additional cement to the volume batched concrete in special circumstances?
   1). Yes ☐
   2). No ☐

10. If your answer is 'Yes', it is to
    1). Increase strength ☐
    2). Increase workability ☐
    3). Reduce segregation & bleeding ☐
    4). All of the above ☐

11. In volume batching what would you do to prevent bulking of fine aggregate?
    1). Keep sand away from rain water ☐
    2). Account for reduction of sand volume ☐
    3). Do not consider it seriously ☐

12. If set of guidelines are prepared for the quality improvement of volume batched concrete, will you accept it
    1). Yes ☐
    2). No ☐
    3). May be ☐

Appendix B – Results of sieve analysis

Fine aggregate

Sieve size (mm)	Finer (%)	Standard value of medium type fine aggregate
2.36	89.47	65-100
1.18	65.87	45-100
0.6	26.10	25-80
0.3	5.95	5-48
0.15	0.43	
0.075	0.01	

Table B1: Fine aggregate percentage

Coarse aggregate

Sieve size (mm)	Finer (%)	Standard value of nominal size of graded aggregate 20 to 5 mm
25	99.23	-
20	92.10	90-100
14	62.10	-
10	42.00	36-60
5	4.00	0-10

Table B2: Coarse aggregate percentage

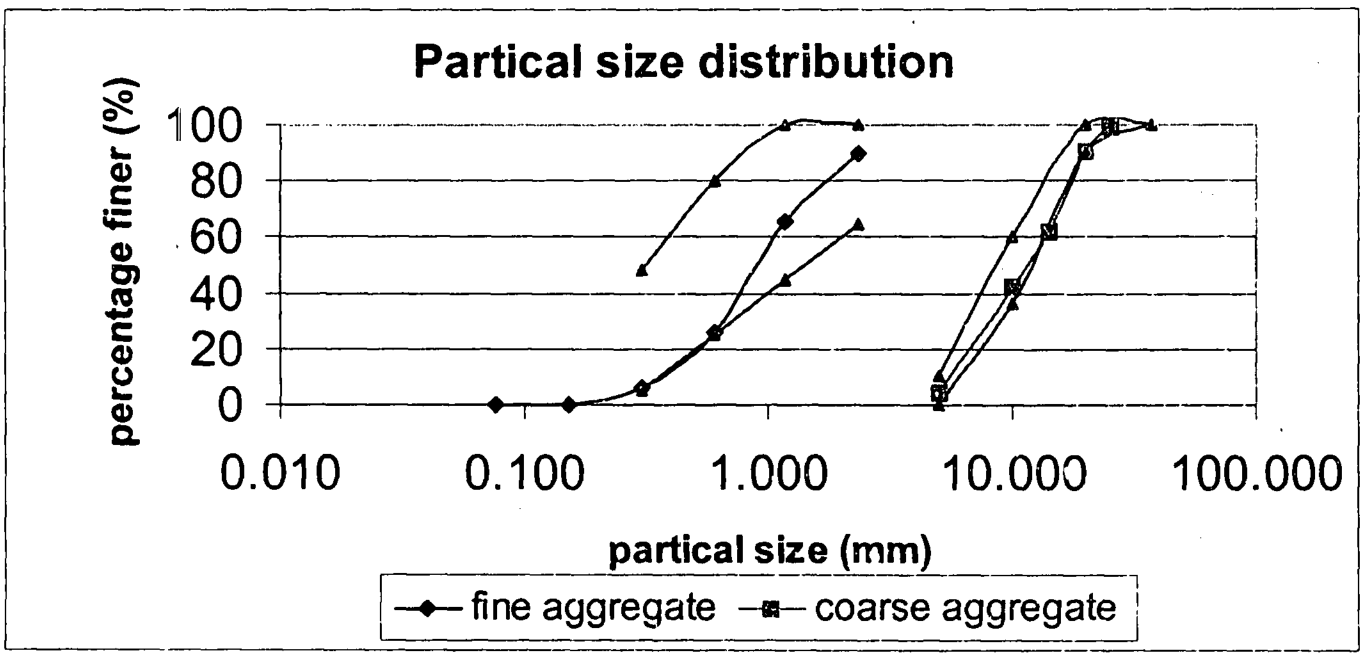


Chart B1: Partical size distribution graphs for coarse and fine aggregate

Appendix C- Results of cube strength

Cement Brand 1

Mix	Dimensions	Load (Tons)	7 days compressive strength in N/mm^2	Average 7 days compressive strength in N/mm^2
Mix 1	150 x 151 x 150	46.50	20.14	20.5
	150 x 150 x 150	48.33	21.07	
	151 x 151 x 150	47.16	20.29	
Mix 2	150 x 150 x 151	57.13	24.91	24.8
	151 x 151 x 150	57.55	24.76	
	150 x 150 x 151	56.72	24.73	
Mix 3	150 x 150 x 150	61.88	26.98	27.0
	151 x 151 x 151	62.57	26.92	
	151 x 150 x 151	62.57	27.10	
Mix 4	150 x 150 x 150	67.66	29.5	29.7
	150 x 150 x 150	68.58	29.9	
	151 x 151 x 151	69.03	29.7	

Table C1: Table showing 7 days compressive strength of brand 1 cement

Mix	Dimensions	Load (Tons)	28 days compressive strength N/mm^2	Average 28 days compressive strength N/mm^2
Mix 1	151 x 151 x 151	67.19	28.91	28.9
	150 x 151 x 151	66.33	28.73	
	150 x 150 x 150	66.65	29.06	
Mix 2	150 x 150 x 150	77.78	33.91	33.8
	151 x 151 x 150	78.10	33.60	
	150 x 151 x 151	78.25	33.89	
Mix 3	150 x 150 x 151	85.14	37.12	37.0
	150 x 151 x 151	85.43	37.10	
	151 x 151 x 150	85.15	36.88	
Mix 4	151 x 151 x 150	94.99	40.86	40.90
	150 x 150 x 151	93.85	40.92	
	150 x 150 x 151	93.85	40.92	

Table C2: Table showing 28 days compressive strength of brand 1 cement

Mix	Dimensions	Load (Tons)	60 days compressive strength N/mm^2	Average 60 days compressive strength N/mm^2
Mix 1	150 x 150 x 151	73.07	31.86	32.0
	150 x 150 x 150	73.69	32.13	
	151 x 151x 150	74.40	32.01	
Mix 2	150 x 150 x 151	85.57	37.31	37.20
	151 x 150 x 150	85.71	37.12	
	150 x 150x 151	85.25	37.17	
Mix 3	151 x 151 x 151	89.62	38.56	38.70
	150 x 150 x 150	89.01	38.81	
	150 x 151x 151	89.42	38.73	
Mix 4	150 x 150 x 150	95.46	41.62	41.40
	150 x 151 x 150	95.29	41.27	
	150 x 151x 151	95.38	41.31	

Table C3: Table showing 60 days compressive strength of brand 1 cement

Cement Brand 2

Mix	Dimensions	Load (Tons)	7 days compressive strength N/mm^2	Average 7 days compressive strength N/mm^2
Mix 1	150 x 150 x 151	44.95	19.6	19.5
	151 x 150 x 150	44.79	19.4	
	150 x 150 x 150	44.72	19.5	
Mix 2	151 x 151 x 151	53.95	23.21	23.6
	150 x 150 x 151	54.38	23.71	
	151 x 150 x 150	55.14	23.88	
Mix 3	150 x 150 x 150	58.05	25.31	25.2
	151 x 150 x 150	59.06	25.41	
	151 x 151 x 150	57.44	24.88	
Mix 4	151 x 150 x 150	62.11	26.9	27.2
	150 x 150 x 150	62.61	27.3	
	150 x 150 x 150	62.84	27.4	

Table C4: Table showing 7 days compressive strength of brand 2 cement

Mix	Dimensions	Load (Tons)	28 days compressive strength N/mm^2	Average 28 days compressive strength N/mm^2
Mix 1	150 x 150 x 150	62.61	27.3	27.7
	151 x 150 x 150	64.88	28.1	
	151 x 150 x 150	63.96	27.7	
Mix 2	150 x 150 x 150	73.62	32.1	32.10
	150 x 150 x 150	73.53	32.06	
	150 x 151 x 151	74.21	32.14	
Mix 3	151 x 150 x 150	83.41	36.13	36.2
	150 x 150 x 150	84.45	36.82	
	151 x 151 x 150	82.86	35.65	
Mix 4	151 x 151 x 150	88.62	38.13	38.0
	150 x 150 x 150	87.64	38.21	
	151 x 150 x 150	86.95	37.66	

Table C5: Table showing 28 days compressive strength of brand 2 cement

Mix	Dimensions	Load (Tons)	60 days compressive strength N/mm^2	Average 60 days compressive strength N/mm^2
Mix 1	150 x 150 x 150	67.43	29.4	29.5
	151 x 150 x 150	68.15	29.32	
	150 x 150 x 151	68.30	29.78	
Mix 2	150 x 151 x 151	81.80	35.43	35.3
	151 x 150 x 150	80.30	35.21	
	150 x 150 x 150	80.87	35.26	
Mix 3	151 x 151 x 150	90.83	39.08	39.1
	150 x 150 x 150	89.93	39.21	
	151 x 150 x 150	90.07	39.01	
Mix 4	150 x 150 x 151	97.04	42.31	42.1
	151 x 150 x 150	97.60	42.27	
	151 x 150 x 150	95.69	41.72	

Table C6: Table showing 60 days compressive strength of brand 2 cement

Cement brand 3

Mix	Dimensions	Load (Tons)	7 days compressive strength N/mm^2	Average 7 days compressive strength N/mm^2
Mix 1	150 x 150 x 151	46.10	20.10	20.1
	150 x 150 x 150	46.61	20.32	
	151 x 150 x 150	45.90	19.88	
Mix 2	151 x 151 x 150	55.95	23.9	24.6
	150 x 150 x 151	57.80	25.2	
	151 x 150 x 150	57.03	24.7	
Mix 3	150 x 150 x 150	65.60	28.6	28.5
	150 x 150 x 151	64.91	28.3	
	151 x 151 x 150	66.47	28.6	
Mix 4	151 x 151 x 150	69.50	29.9	30.1
	150 x 150 x 150	69.50	30.3	
	150 x 150 x 151	69.04	30.1	

Table C7: Table showing 7 days compressive strength of brand 3 cement

Mix	Dimensions	Load (Tons)	28 days compressive strength N/mm^2	Average 28 days compressive strength N/mm^2
Mix 1	151 x 151 x 150	65.54	28.2	28.7
	150 x 150 x 151	66.28	28.9	
	150 x 150 x 150	66.51	29.0	
Mix 2	150 x 150 x 150	76.17	33.21	33.6
	151 x 150 x 151	78.73	34.1	
	150 x 151 x 150	77.32	33.49	
Mix 3	150 x 150 x 151	87.39	38.10	38.2
	150 x 150 x 150	88.87	38.31	
	151 x 151 x 150	88.76	38.19	
Mix 4	151 x 151 x 150	97.39	41.9	42.1
	150 x 150 x 151	97.02	42.3	
	150 x 150 x 151	96.56	42.1	

Table C8: Table showing 28 days compressive strength of brand 3 cement

Mix	Dimensions	Load (Tons)	60 days compressive strength N/mm^2	Average 60 days compressive strength N/mm^2
Mix 1	150 x 150 x 151	75.23	32.8	31.7
	151 x 151 x 150	70.19	30.2	
	150 x 150 x 150	73.62	32.1	
Mix 2	150 x 150 x 151	86.24	37.6	37.5
	150 x 150 x 150	85.78	37.4	
	151 x 151 x 150	87.16	37.5	
Mix 3	151 x 151 x 150	93.67	40.3	40.2
	150 x 150 x 151	93.35	40.7	
	151 x 151 x 150	92.04	39.6	
Mix 4	150 x 150 x 151	99.08	43.2	43.1
	150 x 150 x 150	99.54	43.4	
	151 x 150 x 150	98.59	42.7	

Table C9: Table showing 60 days compressive strength of brand 3 cement

Cement Brand 4

Mix	Dimension	Load (Tons)	7 days compressive strength N/mm^2	Average 7 days compressive strength N/mm^2
Mix 1	150 x 151 x 150	43.18	18.7	18.5
	151 x 151 x 150	43.23	18.6	
	151 x 150 x 151	42.02	18.2	
Mix 2	151 x 150 x 151	54.03	23.4	23.5
	151 x 151 x 151	55.08	23.7	
	151 x 151 x 150	54.39	23.4	
Mix 3	150 x 150 x 150	60.32	26.3	26.3
	150 x 150 x 151	60.78	26.5	
	151 x 151 x 150	60.66	26.1	
Mix 4	150 x 150 x 151	65.14	28.4	28.1
	150 x 150 x 150	63.99	27.9	
	150 x 151 x 150	64.65	28.0	

Table C10: Table showing 7 days compressive strength of brand 4 cement

Mix	Dimension	Load (Tons)	28 days compressive strength N/mm²	Average 28 days compressive strength N/mm²
Mix 1	150 x 151 x 151	60.72	26.3	26.1
	150 x 150 x 150	59.40	25.9	
	151 x 151 x 150	60.66	26.1	
Mix 2	151 x 151 x 150	75.31	32.4	32.2
	150 x 150 x 150	74.08	32.3	
	150 x 150 x 150	73.17	31.9	
Mix 3	151 x 151 x 151	83.91	36.1	36.2
	150 x 150 x 151	83.49	36.4	
	150 x 151 x 151	83.35	36.1	
Mix 4	150 x 150 x 150	88.07	38.4	38.7
	150 x 151 x 151	90.28	39.1	
	150 x 150 x 151	88.53	38.6	

Table C11: Table showing 28 days compressive strength of brand 4 cement

Mix	Dimension	Load (Tons)	60 days compressive strength N/mm²	Average 60 days compressive strength N/mm²
Mix 1	151 x 151 x 150	67.64	29.1	29.2
	150 x 150 x 150	67.66	29.5	
	150 x 150 x 150	66.51	29.0	
Mix 2	151 x 151 x 151	81.35	35.0	35.2
	150 x 150 x 151	80.05	34.9	
	150 x 151 x 151	82.43	35.7	
Mix 3	150 x 151 x 151	88.43	38.3	38.1
	150 x 150 x 150	87.16	38.0	
	151 x 151 x 150	87.16	38.0	
Mix 4	150 x 150 x 150	92.66	40.4	40.7
	150 x 151 x 151	94.43	40.9	
	150 x 150 x 151	93.58	40.8	

Table C12: Table showing 60 days compressive strength of brand 4 cement

Cement brand 3 (For collapse slump)

Mix	Dimensions	Load (Tons)	28 days compressive strength N/mm^2	Average 28 days compressive strength in N/mm^2
Mix 1	150 x 150 x 150 151 x 150 x 151 151 x 151 x 150	46.1 44.56 45.79	20.1 19.3 19.7	19.7
Mix 2	151 x 150 x 150 150 x 150 x 150 151 x 151 x 151	55.64 55.73 56.23	24.1 24.3 24.2	24.2
Mix 3	150 x 151 x 151 150 x 150 x 150 151 x 151 x 150	65.13 65.69 65.89	28.21 28.64 28.35	28.4
Mix 4	150 x 150 x 150 150 x 151 x 151 151 x 150 x 150	73.16 72.96 72.96	31.9 31.6 31.6	31.7

Table C13: Table showing 28 days compressive strength of brand 3 cement at collapse slump

Mix	Dimensions	Load Tons)	60 days compressive strength N/mm^2	Average 60 days compressive strength in N/mm^2
Mix 1	151 x 151 x 151	48.16	20.72	21.4
	151 x 151 x 150	49.99	21.51	
	150 x 151 x 150	50.73	21.97	
Mix 2	150 x 150 x 150	58.88	25.67	25.7
	150 x 150 x 151	59.22	25.82	
	151 x 151 x 150	59.52	25.61	
Mix 3	150 x 150 x 150	75.0	32.70	32.8
	150 x 151 x 151	75.75	32.81	
	151 x 151 x 151	76.44	32.89	
Mix 4	150 x 150 x 150	76.88	33.3	33.3
	150 x 151 x 151	76.59	33.17	
	151 x 151 x 150	77.70	33.43	

Table C14: Table showing 60 days compressive strength of brand 3 cement at collapse slump

Cement brand 4 (For collapse slump)

Mix	Dimensions	Load (Tons)	28 days compressive strength N/mm²	Average 28 days compressive strength in N/mm²
Mix 1	150 x 150 x 150	52.98	23.10	23.0
	151 x 151 x 150	53.39	22.97	
	150 x 151 x 150	52.94	22.93	
Mix 2	150 x 150 x 151	56.44	24.61	24.7
	151 x 150 x 150	57.54	24.92	
	150 x 150 x 150	56.35	24.57	
Mix 3	150 x 150 x 150	67.25	29.32	29.1
	151 x 151 x 150	67.31	28.96	
	150 x 150 x 150	66.56	29.02	
Mix 4	151 x 150 x 151	76.59	33.17	33.2
	150 x 150 x 150	76.42	33.32	
	151 x 151 x 150	76.96	33.11	

Table C15: Table showing 28 days compressive strength of brand 4 cement at collapse slump

Mix	Dimensions	Load (Tons)	60 days compressive strength N/mm²	Average 60 days compressive strength in N/mm²
Mix 1	150 x 151 x 151	54.54	23.62	23.7
	150 x 150 x 150	54.79	23.89	
	150 x 151 x 150	54.47	23.59	
Mix 2	150 x 150 x 151	60.18	26.24	26.2
	150 x 150 x 150	61.32	26.30	
	151 x 150 x 151	60.17	26.06	
Mix 3	150 x 150 x 151	73.78	32.17	32.4
	151 x 151 x 150	75.38	32.43	
	150 x 151 x 151	75.27	32.60	
Mix 4	150 x 150 x 150	77.22	33.67	33.6
	150 x 151 x 151	77.28	33.47	
	151 x 150 x 150	77.72	33.66	

Table C16: Table showing 60 days compressive strength of brand 4 cement at collapse slump

Appendix D

Cement content calculation of different mixes

Bulk density of cement =1400 kg/m^3
Bulk density of sand =1550 kg/m^3
Bulk density of aggregate=1500 kg/m^3

Solid density of cement =3150 kg/m^3
Solid density of sand =2650 kg/m^3
Solid density of aggregate =2600 kg/m3

1:2:4 volume batched concrete with w/c ratio 0.5 (Presently used Grade 20 concrete)

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.035	0.015
Sand	0.071	0.041
Aggregate	0.142	0.082
Water	0.025	0.025
Total volume		0.163

Cement required for m^3 of 1:2:4 concrete =310 kg

1:1.5:3 volume batched concrete with w/c ratio 0.5 (Presently used Grade 25 concrete)

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.035	0.015
Sand	0.053	0.031
Aggregate	0.107	0.062
Water	0.025	0.025
Total volume		0.133

Cement required for m^3 of 1:1.5:3 concrete=375 kg

1:1:2 volume batched concrete with w/c ratio 0.5 (Presently used Grade 30 concrete)

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.035	0.015
Sand	0.035	0.021
Aggregate	0.07	0.041
Water	0.025	0.025
Total volume		0.102

Cement required for m^3 of 1:1:2 concrete=485 kg

1.1:2:4 volume batched concrete with w/c ratio 0.5

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.039	0.018
Sand	0.071	0.041
Aggregate	0.142	0.082
Water	0.025	0.025
Total volume		0.166

Cement required for m^3 of 1.1:2:4concrete=330 kg

1.2:2:4 volume batched concrete with w/c ratio 0.5

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.043	0.019
Sand	0.071	0.041
Aggregate	0.142	0.082
Water	0.025	0.025

Total volume	0.167

Cement required for m^3 of 1.2:2:4concrete=350 kg

1.3:2:4 volume batched concrete with w/c ratio 0.5

Per bag of cement

	Bulk Volume (m^3)	Solid Volume (m^3)
Cement	0.046	0.021
Sand	0.071	0.041
Aggregate	0.142	0.082
Water	0.025	0.025
Total volume		0.169

Cement required for m^3 of 1.3:2:4concrete=380 kg

Appendix E – Results of cube strength with silica fume

Mix	Dimensions	Load (Tons)	7 days compressive strength in N/mm²	Average 7 days compressive strength in N/mm²
$M_1 S_0$	150 x 150 x 151 150 x 150 x 150 150 x 150 x 151	43.81 41.74 41.81	19.10 18.20 18.23	18.51
$M_1 S_1$	151 x 151 x 151 151 x 150 x 151 150 x 150 x 150	52.48 51.49 51.61	22.58 22.30 22.50	22.46
$M_1 S_2$	150 x 150 x 151 150 x 150 x 151 150 x 151 x 150	49.11 50.07 50.26	21.41 21.83 21.77	21.67
$M_2 S_0$	150 x 150 x 150 150 x 150 x 150 151 x 151 x 151	52.25 51.67 53.11	22.78 22.53 22.85	22.72
$M_2 S_1$	150 x 150 x 150 150 x 151 x 150 151 x 151 x 150	55.50 55.69 56.50	24.20 24.12 24.31	24.21
$M_2 S_2$	150 x 151 x 150 150 x 150 x 150 150 x 150 x 150	53.59 52.71 53.00	23.21 22.98 23.11	23.10
$M_3 S_0$	151 x 150 x 150 150 x 150 x 151 150 x 150 x 150	60.42 60.57 60.44	26.17 26.41 26.35	26.31
$M_3 S_1$	151 x 151 x 151 150 x 150 x 150 151 x 151 x 150	69.96 66.99 67.50	30.10 29.21 29.04	29.45
$M_3 S_2$	150 x 150 x 150 150 x 151 x 151 150 x 150 x 150	63.11 64.16 63.53	27.52 27.79 27.70	27.67
$M_4 S_0$	151 x 151 x 151 150 x 150 x 151 150 x 150 x 151	64.71 63.99 64.61	27.84 27.90 28.17	27.97
$M_4 S_1$	151 x 151 x 151 150 x 150 x 150 150 x 150 x 150	66.06 64.66 64.82	28.42 28.19 28.26	28.29
$M_4 S_2$	151 x 151 x 150 150 x 150 x 150 150 x 150 x 150	64.61 64.95 64.54	28.17 28.32 28.14	28.21

Table E2: Table showing 7 days compressive strength of concrete with silica fume

Mix	Dimensions	Load(Tons)	28 days compressive strength N/mm^2	Average 28 days compressive strength in N/mm^2
$M_1 S_0$	150 x 151 x 150 150 x 150 x 151 151 x 151 x 150	67.44 67.50 68.22	29.21 29.43 29.35	29.33
$M_1 S_1$	150 x 150 x 150 150 x 151 x 151 151 x 151 x 150	77.32 77.39 78.03	33.71 33.52 33.57	33.60
$M_1 S_2$	150 x 151 x 151 150 x 150 x 151 150 x 150 x 151	84.32 84.20 84.01	36.52 36.71 36.63	36.62
$M_2 S_0$	150 x 150 x 150 150 x 150 x 151 151 x 150 x 150	82.13 81.26 82.10	35.81 35.43 35.56	35.60
$M_2 S_1$	151 x 151 x 150 150 x 150 x 150 150 x 150 x 150	85.32 86.67 85.99	36.71 37.79 37.49	37.63
$M_2 S_2$	150 x 150 x 150 151 x 150 x 150 151 x 151 x 150	84.45 85.98 86.56	36.82 37.24 37.24	37.10
$M_3 S_0$	151 x 151 x 150 150 x 150 x 151 150 x 150 x 150	90.48 90.62 90.50	38.93 39.51 39.46	39.30
$M_3 S_1$	150 x 150 x 150 151 x 150 x 150 150 x 150 x 150	105.99 105.84 104.90	46.21 45.84 45.74	45.93
$M_3 S_2$	151 x 151 x 150 151 x 151 x 150 150 x 150 x 150	106.26 105.96 104.88	45.72 45.59 45.73	45.68
$M_4 S_0$	150 x 150 x 151 150 x 150 x 151 151 x 151 x 150	109.20 109.45 110.61	47.61 47.72 47.59	47.64
$M_4 S_1$	150 x 150 x 151 151 x 151 x 150 150 x 150 x 150	109.61 110.89 109.72	47.79 47.71 47.84	47.78
$M_4 S_2$	151 x 151 x 151 150 x 150 x 150 150 x 150 x 150	110.88 109.20 109.13	47.49 47.61 47.58	47.56

Table E1: Table showing 28 days compressive strength of concrete with silica fume

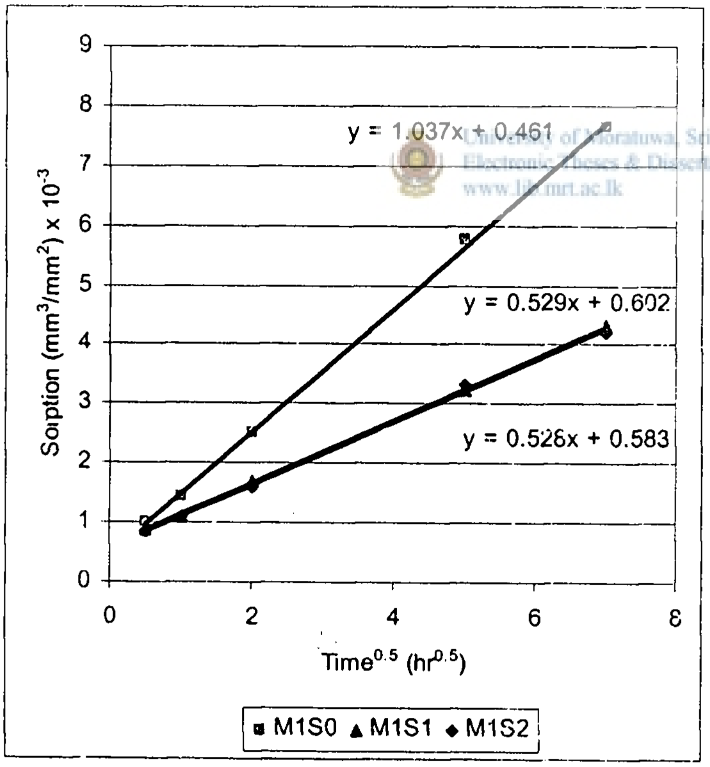
Appendix F – Sorptivity test results

	Absorbed masses (g)				
Time / Specimen	¼	1	4	25	49
$M_1 S_0$	7.5 8.4	10.7 11.9	19.3 20.2	45.0 45.45	58.1 62.0
$M_1 S_1$	6.2 7.5	8.6 8.8	12.1 14.5	24.8 25.9	31.5 36.3
$M_1 S_2$	6.4 7.0	8.4 8.8	12.0 13.2	25.1 27.1	31.4 34.8
$M_2 S_0$	9.1 9.4	12.5 13.4	20.9 22.3	37.4 41.7	47.4 52.9
$M_2 S_1$	9.0 9.2	9.8 10.9	11.4 14.0	22.5 25.1	27.4 29.2
$M_2 S_2$	7.7 6.9	8.4 7.4	13.9 12.3	18.5 16.2	20.8 19.4
$M_3 S_0$	7.3 6.1	8.9 7.2	12.0 11.2	18.9 18.7	21.9 21.6
$M_3 S_1$	7.2 6.2	8.3 6.8	11.4 9.8	17.0 16.3	18.9 18.8
$M_3 S_2$	6.0 5.6	7.1 6.8	8.4 8.1	12.1 11.6	13.6 13.2
$M_4 S_0$	6.5 6.4	7.4 7.3	9.8 9.0	15.1 13.7	19.6 16.9
$M_4 S_1$	6.6 6.8	7.6 7.1	8.0 7.9	11.6 11.3	29.5 28.9
$M_4 S_2$	5.7 5.2	6.1 5.4	6.9 6.2	9.1 8.6	11.0 9.8

Table F1: Table showing absorbed masses (g) vs time (h)

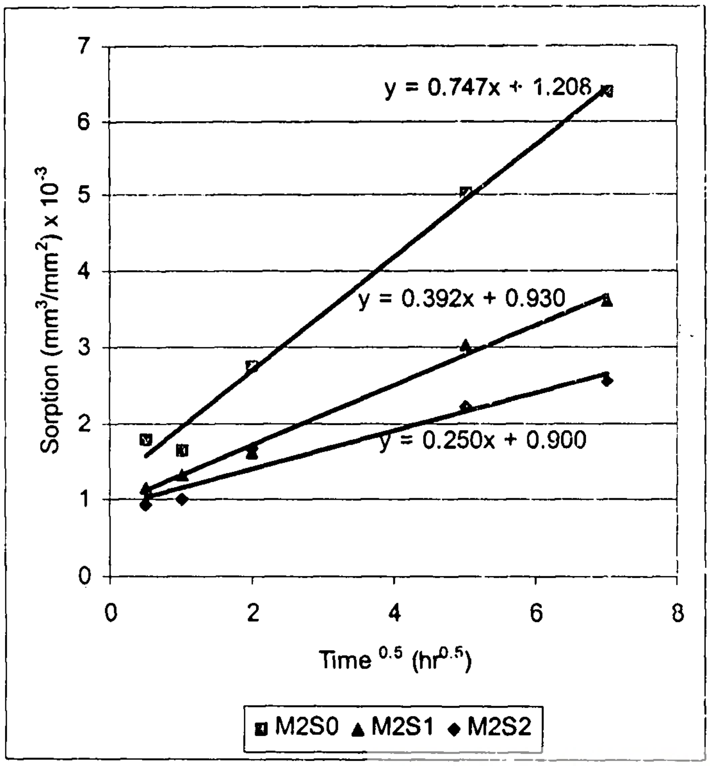
Time (h) / Specimen	Sorption (mm³/mm²) x 10⁻³				
	$^1/_4$	1	4	25	49
$M_1 S_0$	1.012	1.439	2.515	5.758	7.646
$M_1 S_1$	0.872	1.108	1.693	3.225	4.319
$M_1 S_2$	0.856	1.095	1.602	3.324	4.213
$M_2 S_0$	1.177	1.652	2.748	5.034	6.385
$M_2 S_1$	1.158	1.321	1.619	3.028	3.601
$M_2 S_2$	0.933	1.006	1.667	2.209	2.557
$M_3 S_0$	0.854	1.027	1.476	2.394	2.769
$M_3 S_1$	0.856	0.963	1.350	2.120	2.393
$M_3 S_2$	0.737	0.887	1.053	1.507	1.707
M4 S0	0.821	0.935	1.022	1.833	2.325
M4 S1	0.853	0.933	1.013	1.461	1.860
M4 S2	0.697	0.733	0.833	1.127	1.327

Table F1: Table showing sortption in mm^3 / mm^2 vs time



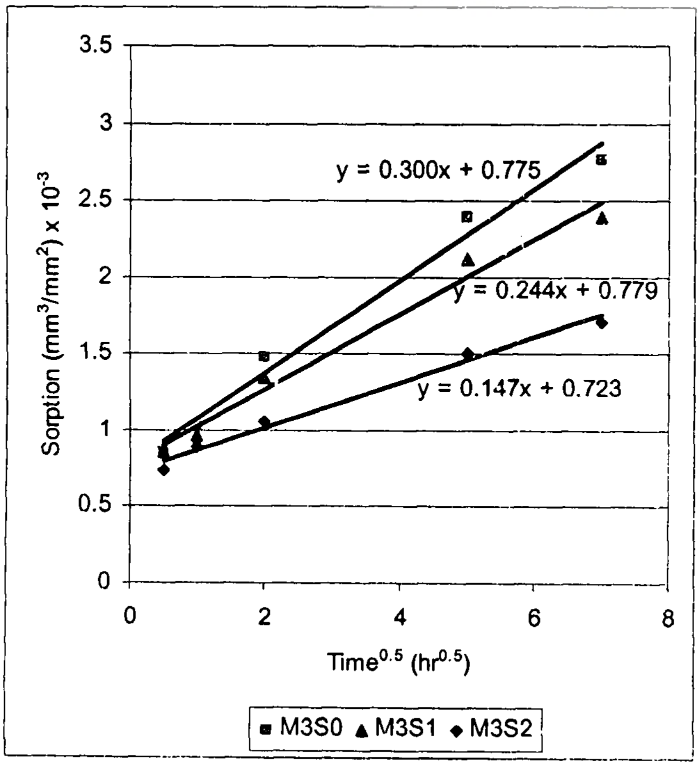
M_1S_0 – 1:2:4 + 0%SF
M_1S_1 – 1:2:4 + 5%SF
$M_1 S_2$ – 1:2:4 + 10%SF

Chart F1: sorptivity results of 1:2:4 concrete for different silica fume



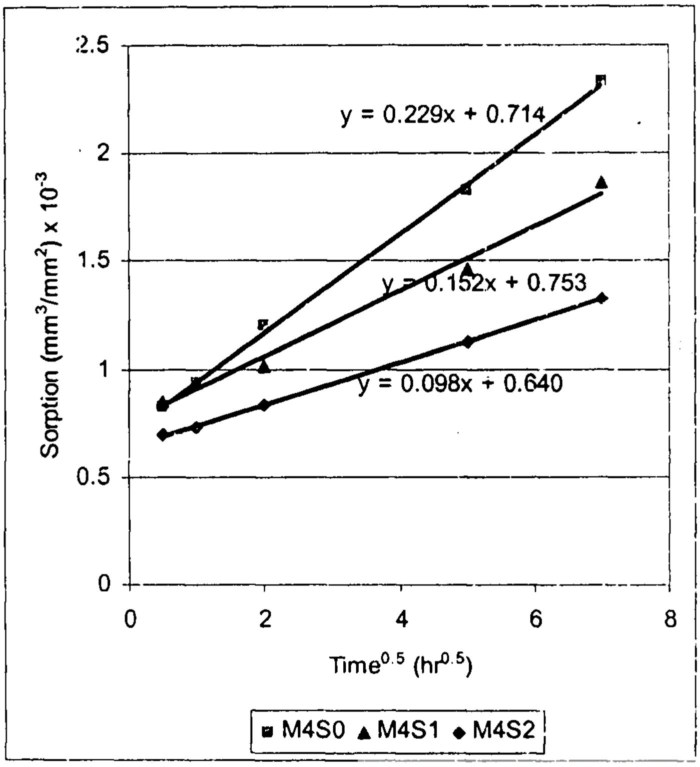
M_2S_0 – 1.1:2:4 + 0%SF
M_2S_1 – 1.1:2:4 + 5%SF
M_2S_2 – 1.1:2:4 + 10%SF

Chart F2: sorptivity results of 1.1:2:4 concrete with different silica fume



M_3S_0 – 1.2:2:4 + 0%SF
M_3S_1 – 1.2:2:4 + 5%SF
M_3S_2 – 1.2:2:4 + 10%SF

Chart F3: Sortptivity results of 1.2:2:4 concrete with different silica fume



M_4S_0 – 1.3:2:4 + 0%SF
M_4S_1 – 1.3:2:4 + 5%SF
M_4S_2 – 1.3:2:4 + 10%SF

Chart F4: sorptivity results of 1.3:2:4 concrete with different silica fume