OPTIMUM SUPERPLASTICIZER CONTENTS OF READY MIXED CONCRETE MADE WITH BLENDED PORTLAND CEMENT

A MASTER'S THESIS

in

Civil Engineering

University of Gaziantep

By

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September 1995

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ABSTRACT

OPTIMUM SUPERPLASTICIZER CONTENTS OF READY MIXED CONCRETE MADE WITH BLENDED PORTLAND CEMENT

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M. S. in Civil Eng.
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September 1995, 271 pages

Using the Gaziantep blended portland cement and locally commercially available sieved and washed river-bed aggregate of three different size fractions and a fine sand of silt size to obtain pumpable mixes with slumps around 60-80 mm to 150-200 mm concretes of classes C14, C16, C20, C25 and C30 were produced. The superplasticizing admixture of modified sodium and calcium lignosulphonate type with some additions of melamine formaldehyde and naphthalene formaldehyde sulphonate condensates contents were 0.0, 0.25, 0.5, 1.0, 1.5, 2.0 and 5.0% by weight of cement. The effects of superplasticizer on fresh and hardened concrete were investigated. In the optimization computer program, the simplex linear formulation was used as the core. To determine the optimum composition, the objective function was chosen as the total investment, operating and maintenance cost related to constituent materials, quality control, transportation, placing and compaction, formwork and scaffolding per cubic metre of concrete in-place. The relative total costs up to and including compaction of concretes show a general trend of increase with increasing slump and concrete class. Minimum costs however, are obtained progressively at higher superplasticizer contents up to about 1.25% at higher slumps.

Key words: Blended cement, superplasticizer, entrained air, pumpability, ready-mixed concrete, optimization

ÖZET

KATKILI PORTLAND ÇIMENTOLU HAZIR BETONLARDA OPTIMUM SUPERAKIŞKANLAŞTIRICI IÇERIGI

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Eylül 1995, 271 sayfa

Katkılı Gaziantep portland çimentosu ve elenmiş, yıkanmış üç değişik tane boyutu dağılımlı yerel dere yatağı agregaları, gerektiğinde beton karışımının pompalanabilmesi için silt boyutunun filler olarak kullanılması ile 60 mm - 80 mm çökmeli C14, C16, C20, C25 ve C30 betonları üretildi. Kondense melamin formaldehid sulfonat ve naftalin formaldehid sulfonat içeren modifiye sodyum ve kalsiyum lignosülfonat esaslı bir süperakışkanlaştırıcı, çimento ağırlığının % 0.0, 0.25, 0.5, 1.0, 1.5, 2.0 ve 5.0 oranlarında kullanıldı. Süperakışkanlaştırıcının taze ve sertleşmiş betonlardaki etkileri araştırıldı. Modelin çekirdek bölümünde doğrusal simpleks optimizasyon formulasyonu kullanıldı. Optimum çözümün belirlenmesinde amaç fonksiyonu 1 m3 betona giren malzemeler, nitelik denetleme, taşıma, yerleştirme, sıkıştırma, kalıp ve iskele ile ilişkili yatırım, işletme ve bakım, bağıl maliyetleri toplamı olarak alındı. Toplam bağıl maliyetler, beton sınıfı ve çökme artışı ile genel bir artış eğilimi gösterdi. En küçük bağıl maliyetler yüksek çökmelerde %1.25'e varan superakışkanlaştırıcı içeriklerinde elde edildi.

Anahtar Kelimeler:Katkılı çimento, superakışkanlaştırıcı, sürüklenmiş hava, pompalanabilme, hazır beton, optimizasyon

ACKNOWLEDGEMENT

First of all, I would like to thank Assoc. Prof. Abdurrahman GÜNER for his invaluable helps, supervision and constructive suggestions.

I am particularly grateful to my family for their patience during my B.S. and M.S. educations.

I wish to thank Irfan BAL and Asım KAPISIZ for their helps in the Materials of Construction laboratory.

ATMAZ BETON and BALPA companies are acknowledged for supplying the materials and information.

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1. CONCRETE

1.1. INTRODUCTION

Concrete is a man-made composite the major constituent of which is natural aggregate, such as gravel and sand or crushed rock. Alternatively artificial aggregates, for example, blast-furnace slag, expanded clay, broken brick and steel shot may be used where appropriate. The other principal constituent of concrete is the binding medium used to bind the aggregate particles together to form a hard composite material of adequate mechanical strength and durability. The most commonly used binding medium is the product formed by a chemical reaction between mineral based cement and water.

In its hardened state concrete is a rock-like material with a high compressive strength. By virtue of the ease with which fresh concrete in its plastic state may be moulded into virtually any shape it may be used to advantage architecturally or solely for decorative purposes. In addition, concrete requires little maintenance. Due to all these and other mechanical and physical properties of concrete, it is used structurally in buildings for foundations, columns, beams and slabs, in shell structures, bridges, roads, dams and so on.

The quality of concrete, as dictated by the project requirements, depends on the quality and proportions of the constituent materials [6, p 108].

In order to obtain a strong, durable and economical concrete mix, it is necessary to understand the characteristics and behaviour of the ingredients. The ingredients of the concrete are most often classified into two groups, namely active and inactive. The *active* or binding phase consists of cement and water, whereas inactive group comprises fine and coarse aggregates, ignoring the alkali aggregate reactivity related to durability. The inactive group is also sometimes called the *inert phase* [3, p 5].

1.2. CONCRETE MAKING MATERIALS

1.2.1 Cement

The different cements used for making concrete are finely ground powders and all have the important property that when mixed with water a chemical reaction (*hydration*) takes place which, in time, produces a very hard and strong binding medium for the aggregate particles. In the early stages of hydration, while in its plastic stage, cement mortar gives to the fresh concrete its cohesive properties.

Portland cement was developed in 1824 and derives its name from Portland limestone in Dorset because of its close resemblance to this rock after hydration has taken place. The basic raw materials used in the manufacture of Portland cements are calcium carbonate, found in calcareous rocks such as limestone or chalk, and silica, alumina and iron oxide found in argillaceous rocks such as clay or shale. Marl, which is a mixture of calcareous and argillaceous materials, can also be used [6, p 111].

In most countries, specifications for Portland cement do not allow any addition to clinker other than gypsum and water. With moves to save energy, the idea to add some *inert filler* to portland cement has been advanced; this then would be *Blended Portland Cement*. The most likely filler is limestone ground to the same fineness as Portland Cement, the proportion of the addition being *10* to *15* per cent of the total.

The filler has no cementitious value but it improves workability, and Blended Portland Cements are extensively used in *low-strength* concrete. Indeed, one can argue that, for many purposes where *high-strength* concrete is not needed, the *high-quality Portland cements* are *too good,* so that there is intrinsic merit, and not only energy saving, in this development [1, p 84].

It may be further noted that blended cements would automatically provide an adequate amount of fines. The presence of fines of all provenance (i.e. aggregate, filler, and cement) can be assured by using the total content of particles smaller than *125* μm, given in Table 1.1.

The volume of entrained air can be taken as equivalent to one-half the volume of fines and should be included in the above figures.

Table 1.1 Total Fines Requirement of Concrete as a Function of Maximum Aggregate Size [1, 173]

Maximum aggregate size , mm	Absolute volume of fines (<125 μm) as fraction of volume of concrete
8	0.165
16	0.140
32	0.125
60	0.110

1.2.2. Water

Water used in concrete, in addition to reacting with cement and thus causing it to set and harden, also facilitates mixing, placing and compacting of the fresh concrete. It is also used for washing the aggregates and for curing purposes. The effect of water content on the properties of fresh and hardened concrete is discussed in *Section 2.1.2 and 2.2.2.* In general water fit for drinking, such as tap water, is acceptable for mixing concrete. The impurities that are likely to have an adverse effect when present in appreciable quantities include silt, clay, acids, alkalis and other salts, organic matter and sewage. The use of seawater does not appear to have any adverse effect on the strength and durability of Portland cement concrete but it is known to cause dampness, efflorescence and staining and should be avoided where concrete with a good appearance is required. Seawater also increases the risk of corrosion of steel and its use in reinforced concrete is not recommended.

The use of impure water for washing aggregates can adversely affect strength and durability if it deposits harmful substances on the particles. In general, the presence of non corrosive impurities in the curing water does not have any harmful effect, although it may spoil the appearance of concrete. Water containing appreciable amounts of acids or organic materials should be avoided [6,p 131].

1.2.3. Aggregate

Since about three-quarters of the volume of concrete is occupied by aggregate, its quality is of considerable importance. Not only may the aggregate limit the strength of concrete, as weak aggregate cannot produce strong concrete, but the properties of aggregate greatly affect the durability and structural performance of concrete.

Aggregate was originally viewed as an inert material dispersed throughout the cement paste largely for economic reason. It is pertinent to take an opposite view and to look on aggregate as a building material connected into a masonry construction. In fact, aggregate is not truly inert and its physical, thermal, and sometimes also chemical properties influence the performance of concrete.

Aggregate is cheaper than cement and it is, therefore, economical to put into the mix much of the former and as little of the latter as possible. But economy is not the only reason for using aggregate: it confers considerable technical advantages on concrete, which has a higher volume stability and better durability than the cement paste alone.

The size of aggregate used in concrete ranges from tens of millimetres down to particles of the order of a tenth of a millimetre in cross-sections. The maximum size actually used varies but in any mix particles of different sizes are incorporated, the particle size distribution being referred to as *grading*. In making low-grade concrete, aggregate from deposits containing a whole range of sizes, from the largest to the smallest, not necessarily complying with any type grading, is sometimes used; this is referred to as *all-in aggregate*. The alternative, very much more common, and always used in the manufacture of good quality concrete, is to obtain the aggregate in at least two size groups, the main division being between *fine aggregate*, often called ***sand***, *not larger than about 4 to 5 mm*, and ***coarse aggregate***, which comprises material *at least about 4 to 5 mm* in size. Sand is generally considered to have a lower size limit of about *0.07 mm* or a little less. Material between *0.06 mm and 0.002 mm* is classified as ***silt***, and particles smaller still are termed clay [1, p 118].

1.2.4. Admixture

Admixtures are substances introduced into a batch of concrete, during or immediately before its mixing, in order to improve the properties of the fresh or hardened concrete or both. Although certain finely divided solids, such as pozzolans and slags, fall within the above broad definition of admixtures they are distinctly different from what is commonly regarded as the main stream of admixtures and therefore should be treated separately.

In general, the changes brought about in the concrete by the use of admixtures are effected through the influence of the admixtures on hydration, liberation of heat, formation of pores and the development of the gel structure. *Concrete admixtures should only be considered for use when the required modifications cannot be made by varying the composition and proportion of the basic constituent materials, or when the admixtures can produce the required effects more economically.*

Since admixtures may also have detrimental effects, their suitability for a particular concrete should be carefully evaluated before use, based on a knowledge of their main active ingredients, on available performance data and on trial mixes. *The specific effects of an admixture generally vary with the type of cement, mix composition, ambient conditions (particularly temperature) and its dosage.* Since the quantity of admixture used is both small and critical the required dose must be carefully determined and administered [6, p 131].

According to the characteristic effects produced by them, the admixtures may be broadly classified as:

(a) accelerating admixtures,
(b) retarding and water reducing admixtures,
(c) grouting admixtures,
(d) air-entraining admixtures,
(e) air-detraining admixtures,
(f) gas forming admixtures,
(g) expansion-producing admixtures,
(h) waterproofing and permeability reducing admixtures,
(i) corrosion inhibiting admixtures,
(j) fungicidal, germicidal and insecticidal admixtures,
(k) bonding admixtures,
(l) pozzolanic admixtures,
(m) colouring admixtures or pigments,
(n) concrete hardening admixtures, and
(o) superplasticizers [3, p 46].

Water-reducing agents and superplasticizers are discussed below since their use in concrete constitutes the subject of this work.

1.2.4.1. Water-Reducing agents

The water-reducing admixtures are the group of products which possess as their primary function the ability to produce concrete of a given workability, as measured by a suitable method such as slump or compaction factor, at a lower water content and/or water/cement ratio than that of a control concrete containing no admixture.

The lignosulphonates formed the basis of almost all the available water-reducing admixtures until 1950s when the hydroxycarboxylic acid salts were developed which have grown to occupy a significant but, nevertheless, still a minority position in this product group. Materials such as glucose and hydroxylated polymers obtained by the partial hydrolysis of polysaccharides have been widely used in North America. The polymers usually have a low molecular weight and contain glycoside units ranging from 3-25. In addition, other chemical admixture types have been included into the water-reducing admixtures' formulations to produce five types within this category.

The *normal water-reducing* admixtures allow a reduction in the water content at a given workability and/or cement content without significantly affecting the *setting characteristics* of the concrete. In practice, this effect can be utilized in three ways:

(a) By the addition of the admixture with a reduction in the water/cement ratio, a concrete having the same workability as the control concrete can be obtained, with unconfined compressive strengths at all ages which exceed those of the control.

(b) If the admixture is added directly to a concrete as part of the gauging water with no other changes to the mix proportions, a concrete possessing similar strength development characteristics is obtained, yet having a greater workability than the control concrete.

(c) A concrete with similar workability and strength development characteristics can be obtained at lower cement contents than a control concrete without adversely effecting the durability or engineering properties of the concrete.

In all three ways of use, this type of admixture can be regarded as a *cement "saver"* as illustrated in *Fig. 1.1.*

Corresponding no-admixture mixes are, therefore, concrete mixes having the same workability and 28-day strength characteristics, but the mix containing the water-reducing admixture will have a lower cement content than the other mix. In practice, of course, the parameters of workability and strength are dictated by the requirements of the particular situation; in areas of high steel content, a high workability will be required,

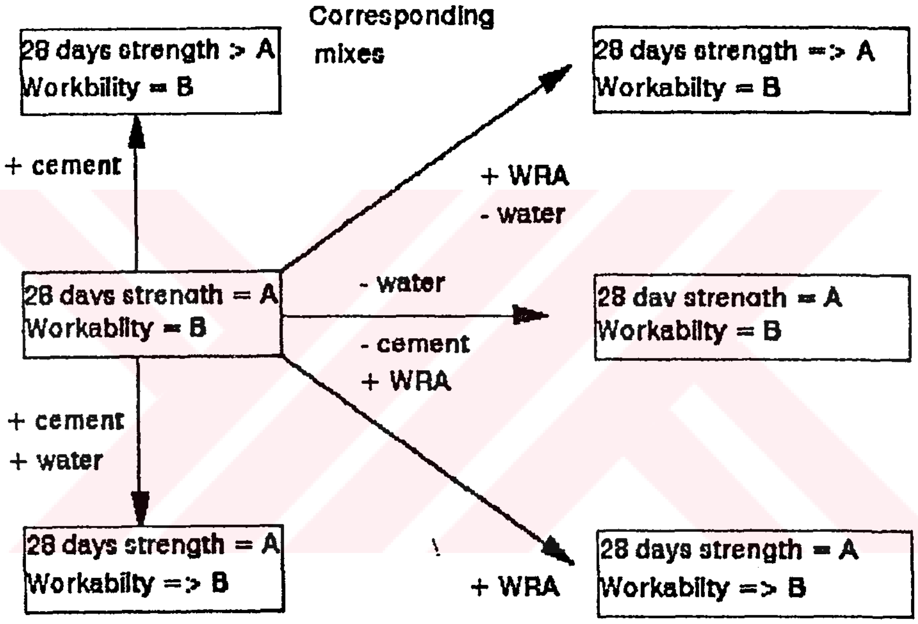


Fig 1.1 The Concept of Corresponding Mixes [2, p 2]

whilst in the production of extruded prestressed lintels, a very low workability is needed. In both cases the strength requirements will be dictated by the load-bearing characteristics of application. Thus in comparing any properties of admixture-containing concretes, the results of corresponding no-admixture mixes should be studied, whether the investigation be related to strength, durability factors or statistical considerations, such as standard deviation.

Although the pictorial comparison shown in *Fig. 1.1* and discussed above is true at low and average cement contents up to about *350 kg/m*^{3}, it is more difficult to obtain higher strengths and workability by further increasing the cement content. It is in this area that the hydroxycarboxylic acid water-reducing admixtures are particularly beneficial, enabling considerable side effects of large cement increments be compensated.

The other members of the water-reducing admixture group possess some other functions which could not be obtained by mix design considerations.

The *accelerating water-reducing* admixtures, whilst possessing the water-reducing capability of the "*normal*" category, give higher strengths during the earlier hydration period, which is particularly useful at lower temperatures.

The *retarding water-reducing* admixtures again behave in a similar manner to the "*normal*" materials and are often of similar chemical composition used at a higher dosage level, but extend the period of time when the concrete is in the workable state. This means that the time available for transport, handling and placing is lengthened. In fact, although a few materials are available which exert only a retarding influence on concrete and have little or no water-reducing capacity, the vast majority (about 95%) of materials called "retarders" are actually retarding water-reducing admixtures.

The *air-entraining water-reducing* agents posses the ability to entrain microscopic air bubbles (of about 0.2 mm size) into the cement paste whilst allowing a reduction in the water/cement ratio greater than that which would be obtained by the air entrainment itself. They are available in the "*normal*" and "*retarding*" form and also fall into two types depending on the level of air entrainment; the first type entrains only about *1 to 2%* of additional air and is normally used to increase the internal surface of the concrete to redress any deficiencies in fine aggregate grading. The second type results in concrete containing *3 to 6%* of air and is used to enhance the durability of the concrete to freeze-thaw conditions.

The advantages of using this type of material rather than a straight air-entraining agent are based mainly on minimizing the deleterious effect that air entrainment has on compressive strength. Thus, in a typical concrete mix, up to 3% air can be entrained without any alteration to the mix design or reduction in compressive strength when an air-entraining water-reducing admixture is used [2, p 1].

1.2.4.2. Superplasticizers

These are also called "*high-range water-reducing admixtures*". Chemically, they are sulphonated melamine formaldehyde condensates and suplhonated naphthalene formaldehyde condensates, the latter being probably the somewhat more effective (and more expensive) of the two in dispersing the cement and generally having also some retarding properties. At a given water/cement ratio, this dispersing action increases the workability of concrete, typically by raising the slump from *75 mm* to *200 mm*, the mix remaining cohesive. (The improvement in workability is smaller at high temperatures.) The resulting concrete can be placed with little or no compaction and is not subject to excessive bleeding or segregation. Such concrete is termed "*flowing concrete*" and is useful for placing in very heavily reinforced sections, in inaccessible areas, in floor or road slabs and also where very rapid placing is desired.

The second use of superplasticizers is in the production of concrete of normal workability but with an extremely high strength owing to a very substantial reduction in the water/cement ratio. Generally speaking, *superplasticizers can reduce the water content for a given workability by 25 to 35 per cent (compared with half that value in the case of conventional water-reducing admixtures), and increase the 24-hour strength* *by 50 to 75 per cent;* and even greater increase occurs at earlier ages.

When the strength at later ages is of primary importance, superplasticizers can be used in concrete with partial fly-ash replacement of cement.

The plasticizing action of superplasticizers is of short duration: after some *30 to 90 minutes* the workability returns to normal. For this reason, the superplasticizer should be added to the mix immediately prior to placing; usually, conventional mixing is followed by the addition of superplasticizer and a short period of additional mixing. In the case of ready-mixed concrete, a *2.5-minute* re-mixing period is essential depending on the type and number of revolutions of the mixer. Re-tempering with an additional dose is not recommended. Superplasticizers can be used at comparatively high dosages. They do not markedly change the surface tension of water, their action being the dispersion of cement agglomerates normally found when cement is suspended in water. These admixtures are thought to be adsorbed on the surface of cement and of other very fine particles, causing them to become mutually repulsive as a result of the anionic nature of superplasticizers, which causes the cement particles to become negatively charged (*See Appendix A.2.*).

The use of superplasticizer with an air-entraining admixture requires caution as sometimes the actual amount of entrained air is reduced by the superplasticizer. Specially modified superplasticizers have been developed and these seem to produce satisfactory air-entrained concrete with conventional air-entraining agents. The only real disadvantage of superplasticizers is their relatively high cost [2, p 4].

1.3. SPECIAL CONCRETES

1.3.1. Ready-mixed Concrete

If instead of being batched and mixed on site, concrete is delivered ready for placing from a central plant, it is referred to as ready-mixed or pre-mixed concrete. This type of concrete is used extensively as it offers numerous advantages in comparison with the ordinary method of manufacture.

Ready-mixed concrete is particularly useful on congested sites or in road construction where little space for the mixing plant and for extensive aggregate stockpiles is available, but perhaps the greatest single advantage of ready-mixed concrete is that it may be made under better conditions of control than are normally possible on any but large construction sites. Control has to be enforced but, since central mixing plant operates under near-factory conditions, a really close control of all operations of manufacture of fresh concrete is possible. In a modern batching and mixing plant, interlocking prevents incorrect batching quantities, and sometimes a printed record of weights of ingredients of every batch is made. Proper care during transportation of the concrete is also ensured by the use of agitator trucks, but the placing and compaction remain, of course, the responsibility of the personnel on the site. Ready -mixed concrete can be considered to be more in the nature of a factory-made product so that a great deal of uncertainty and variability associated with the production of concrete on many a site is removed.

There are two principal categories of ready-mixed concrete. In the first, the mixing is done at a central plant and the mixed concrete is then transported, usually in an agitator truck which revolves slowly so as to prevent segregation and undue stiffening of the mix. Such concrete is known as central-mixed as distinct from the second category - transit mixed or truck-mixed concrete. Here, the materials are batched at a central plant but are mixed in a mixer truck either in transit to the site or immediately prior to the concrete being discharged. Transit-mixing permits a longer haul and is less vulnerable in case of delay, but the capacity of a truck used as a mixer is only about three-quarters of the same truck used solely to agitate pre-mixed concrete.

Sometimes, the concrete is partially mixed at a central plant in order to increase the capacity of the agitator truck. The mixing is completed en route. Such concrete is known as shrink-mixed concrete. Truck mixers usually have a capacity of 6 m^3 but 7.5 m^3 trucks also exist.

The main problem in the production of ready-mixed concrete is maintaining the workability of the mix right up to the time of placing. Concrete stiffens with time and handling ready-mixed concrete often takes quite a long while. The stiffening may also be aggravated by prolonged mixing and by a high temperature. In the case of transit-mixing, water need not be added till nearer the commencement of mixing, but the time during which the cement and moist aggregate are allowed to remain in contact should be limited to about 90 minutes, although an amendment to BS 5328:1976 allows 2 hours. Where no agitation is available the figure is reduced to 1 hour, also if the temperature of the concrete is above 30°C at the time of compaction the period above is reduced to 1 hour. It is usual also to limit the total number of revolutions during both mixing and agitating to approximately 300. However, agitating up to 6 hours need not adversely affect the strength of concrete provided the mix remains sufficiently workable for full compaction. Unless, however, the initial workability is high, the stiffening caused by prolonged agitation would result in a concrete of very low workability, especially in hot weather, when a high loss of water by evaporation takes place in addition to the loss of free water by hydration of cement. For this reason, concrete is sometimes re-tempered by the addition of water immediately before discharge; the workability is thus restored but it must be realized that the resultant compressive strength will be affected by the amount of water added to the mix [1, p 234].

1.3.2. Pumped Concrete

Up to here we dealt with ready-mixed concrete, the details of the means of transporting and placing are not considered. An exception should be made in the case of pumping of concrete since this means of transportation requires the use of a mix with special properties.

Pumps of different sizes and different types are available and likewise pipes of various diameter are used but the pipe diameter must be at least three times the maximum aggregate size. Aluminium pipes must not be used because aluminium reacts with the alkalis in cement and generates hydrogen in addition to abrasion and alkali corrosion. This gas introduces voids in the hardened concrete with consequent loss of strength, unless the concrete is placed in a confined space.

The main advantages of pumping concrete are that it can be delivered to points over a wide area otherwise not easily accessible, with the mixing plant clear off the site; this is especially valuable on congested sites or in special applications such as tunnel linings, etc. Pumping delivers the concrete direct from the mixer to the form and so avoids double handling. Placing can proceed at the rate of the output of the mixer and is not held back by limitations of the transporting and placing equipment. A significant proportion of ready-mixed concrete is nowadays pumped.

Furthermore, pumped concrete is unsegregated but of course in order to be able to be pumped the mix must satisfy certain requirements. It might be added that unsatisfactory concrete cannot be pumped so that any pumped concrete is satisfactory as far as its properties in the fresh state are concerned. Control of the mix is afforded by the force required to stir it in the hopper and by the pressure required to pump it.

Concrete which is to be pumped must be well mixed before feeding into the pump and sometimes remixing in the hopper by means of a stirrer is carried out. The mix must not be harsh or sticky, too dry or too wet, i.e. its consistency is critical. A slump of between 40 and 100 mm or a compaction factor of approximately 0.90 to 0.95 or VeBe time of 3 to 5 sec is generally recommended, but pumping produces a partial compaction so that at the point of delivery the slump may be decreased by 10 mm to 25 mm. With a lower water content, the solid particles, instead of moving longitudinally in a coherent mass in suspension, would exert pressure on the walls of the pipe. When the water content is at the correct, or critical, value friction develops only at the surface of the pipe and in a thin, 1 to 2.5 mm, layer of the lubricating mortar. Thus nearly all the concrete moves at the same velocity, which is called "*plugged flow*". It is possible that the formation of the lubricating film is aided by the fact that the dynamic action of the piston is transmitted to the pipe, but such a film is also caused by steel trowelling of a concrete surface. To allow for the film in the pipe a cement content slightly higher than otherwise would be used is desirable. The magnitude of the friction developed depends on the consistence of the mix, but there must be no excess water as segregation would result.

It may be useful to consider the problem of friction and segregation in more general terms. In pipe through which a material is pumped, there is a pressure gradient in the direction of flow due to two effects: head of the material and friction. This is another way of saying that the material must be capable of transmitting a sufficient pressure to overcome all resistances in the pipeline. Of all the components of concrete, it is only water that is pumpable in its natural state, and it is the water, therefore, that transmits the pressure to the other mix components.

Two types of blockage can occur. In one, water escapes through the mix so that pressure is not transmitted to the solids, which therefore do not move. This occurs when the voids in the concrete are not small enough or intricate enough to provide sufficient internal friction within the mix to overcome the resistance of the pipeline. Therefore, an adequate amount of closely packed fines is essential to create a "*blocked filter*" effect, which allows the water phase to transmit the pressure but not to escape from the mix. In other words, the pressure at which segregation occurs must be greater than the pressure needed to pump the concrete. It should be remembered of course that more fines mean a higher surface area of the solids and therefore a higher frictional resistance in the pipe.

We can see thus how the second type of blockage can occur. If the fines content is too high, the friction resistance of the mix can be so large that the pressure exerted by the piston through the water phase is not sufficient to move the mass of concrete, which becomes stuck. This type of failure is more common in the high strength mixes or in mixes containing a high proportion of very fine material such as crusher dust or fly ash, while the segregation failure is more apt to occur in medium or low strength mixes with irregular or gap grading.

The optimum situation, therefore, is to produce maximum frictional resistance within the mix with minimum void sizes, and minimum frictional resistance against the pipe walls with a low surface area of the aggregate. This means that the coarse aggregate content should be high, but the grading should be such that there is a low void content so that little of the very fine material is required to produce the "*blocked filter*" effect or "*plugged flow*".

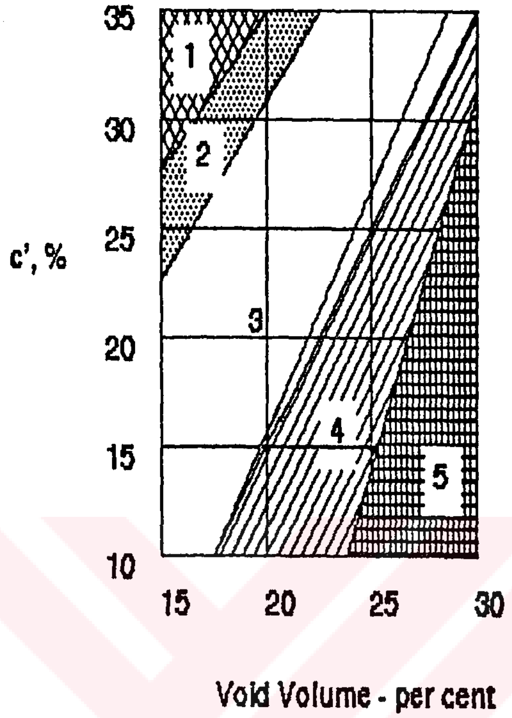
The size fractions which have the largest influence on the void content of practical mixes are: *2 mm to 4 mm*, *250 μm to 500 μm*, and *125 μm to 250 μm*. Of these, the first one is the most significant as inadequate amount of material between *2 mm and 4 mm* results in a high void content of the aggregate and hence leads to difficulties in pumping.

For concretes with maximum aggregate size of *20 mm*, the optimum fine aggregate content lies between *40 and 45 per cent*, and the material finer than *250 μm* should represent *15 to 30 per cent* of the weight of fine aggregate.

In mixes with low cement contents, an adequate amount of material passing the *125 μm sieve* is necessary to achieve the fine sieve effect. On the other hand, when the cement content of the mix is high, a high content of fines is also necessary in order to increase the surface area and to increase friction. Generally, the proportion of fine aggregate which passes the *150 μm sieve* should be about *3 per cent.* This material may be the finer fraction of sand or a suitable additive, such as tuff or trass. This fine material gives continuity in grading right down to the cement fraction but still avoids a very high pipe friction.

The pattern of the effect of the relation between the cement content and void content on pumpability is shown in *Figure 1.2.* However, it is only fair to add that theoretical calculations are not very helpful because the shape of the aggregate particles influences their void content.

The shape of the aggregate influences the suitability of a mix for pumping. Natural sands are often particularly suitable for pumping because of their rounded shape and also because the true grading is more continuous than with crushed aggregate where within each size fraction there is less variety in size. For both these reasons, the void content is low. On the other hand, using combinations of size fractions of crushed



Zones:

1. Not pumpable due to excessive friction
2. Pumpable under high pressure
3. Pumpable
4. Pumpable with increased viscosity of water
5. Not pumpable due to segregation

Fig 1.2 Pumpability of Concrete in Relation to Cement and Void Content (m^3/m^3 *conc.) of Aggregate [2,p 241]*

aggregate, a suitable void content can be achieved. However, care is required as many crushed fines are deficient in the size fractions *250 μm to 500 μm* but have excess of material smaller than *125 μm*. When using crushed coarse aggregate, it should be remembered that crusher dust may be present and this should be taken into account in considering the grading of the fine aggregate. Generally, with crushed coarse aggregate, the fine aggregate content should be increased by about *2 per cent*.

If the aggregate surface is sealed, then it pumps as well as normal aggregate. But if the aggregate surface is porous then the internal voids may not become fully saturated even on thorough wetting. As a result, when pressure is applied in the pipeline, the air in these voids is compressed, and water is forced into the pores with the result that the mix becomes too dry and stiff. If pumping is stopped and pressure removed, water is discharged from the aggregate; this water may carry with it the fine material so that a plug forms on resumption of pumping. Some of the aggregate may also become crushed by pumping. Nevertheless, with special admixtures, which have a thickening as well as dispersing effect, lightweight aggregate concrete can be successfully pumped over moderate distances.

Under a high pumping pressure, the air becomes compressed and no longer aids the mix by its "*ball-bearing*" effect. The friction rises and so does the pressure; the air becomes compressed further so that the workability drops even more. If the pipeline is long enough, the reduction in volume of the air under pressure can absorb the entire stroke of the piston so that no concrete will come out at the delivery end. For this reason, air-entrained concrete is usually pumped only over short distances: about 45 m [1, p 237].

2. PROPERTIES OF FRESH CONCRETE

2.1. INTRODUCTION

Fresh concrete is a mixture of water, cement, aggregate and admixture (if any). After mixing, operations such as transporting, placing, compacting and finishing of fresh concrete can all considerably affect the properties of hardened concrete. It is important that the constituent materials remain uniformly distributed within the concrete mass during the various stages of its handling and that full compaction is achieved. When either of these conditions is not satisfied the properties of the resulting hardened concrete, for example, strength and durability, are adversely affected.

2.2. WORKABILITY

The diverse requirements of *mixability, stability, transportability, placability, mobility, compactability and finishability* of fresh concrete are collectively referred to as ***workability***. The workability of fresh concrete is thus a composite property. The optimum workability of fresh concrete varies from situation to situation, e.g., the concrete which can be termed as workable for pouring into large sections with minimum reinforcement may not be equally workable for pouring into heavily reinforced thin sections.

Sometimes the terms consistency and plasticity are used to denote the workability of a concrete mix. The *consistency* of the mix really means the wetness of the mix, and a wetter mix need not have all the above desired properties. On the other hand, an extremely wet mix may cause segregation and may be difficult to place in mould. *Plasticity* is the cohesiveness of the mix to hold the individual grains together by the cement matrix [3, p 61].

2.2.1. Factors Affecting Workability

In the concrete comprising a cement-aggregate-water system, the aggregates occupy approximately 70 to 75 per cent of the total volume of concrete and economy demands that the volume of aggregates should be as large as possible. The total specific area of the aggregate is to be minimized to the extent possible by proper choice of size, shape and proportion to minimize the void content, and such a mixture will need more water for lubricating effects to overcome the reduction in mobility due to dense packing of particles resulting in dilatancy. The water/cement ratio in itself determines the intrinsic properties of cement paste and the requirements of workability such that there is sufficient cement paste to surround the aggregate particles as well as fill the voids in the aggregate. It has been noticed that the change in the measured value of workability due to relative change in water content in concrete is independent of the composition of concrete within wide limits. This is reflected in the empirical water requirement formula $W = \alpha(10-k)$ (where k is the fineness of the combined aggregate and α is a coefficient related to workability and surface texture of aggregate) suggested by standards. An increase of water content results in monotonous increase in workability but eventually a stage is reached where segregation and bleeding occur in fresh concrete, and use of higher water content will result in the more serious problems of shrinkage and creep of hardened concrete. However, the water content is limited to some maximum value given by the water/cement ratio which is dependent on the target design strength of hardened concrete, making it imperative to study the effect on workability of other factors [3, p 65].

2.2.2. Measurement of Workability

Unfortunately, *there is no acceptable test which will measure workability directly*. Numerous attempts have been made, however,. to correlate workability with some easily determinable physical measurement, but none of these is fully satisfactory although they may provide useful information within a range of variation in workability. The empirical tests widely used are:

(a) the slump test,

(b) the compacting factor test

(c) the VeBe consistency test

(d) the flow table test,

(e) Nasser's K-probe test,

The *slump test* is perhaps the most widely used, primarily because of the simplicity of the apparatus required and the test procedure [25 and 34]. The slump test indicates the behaviour of a compacted concrete frustum of a cone under the action of gravitational forces. The slump cone is placed on a horizontal and nonabsorbent surface and filled in three equal layers of fresh concrete, each layer being tamped 25 times with a standard tamping rod. The top layer is struck off level and the mould lifted vertically without disturbing the concrete cone. The subsidence of concrete in millimetres is termed the *slump*. The concrete after the test when slumps evenly all around is called ***true slump***. In the case of very lean concrete, one-half of the cone may slide down the other which is called a ***shear slump***; or it may ***collapse*** in case of very wet concretes. The slump test is essentially a measure of consistency or the wetness of the mix. The test is suitable only for concretes of medium to high workabilities. For very stiff mixes having zero slump, the slump test does not indicate any difference in concretes of different workabilities. It must be appreciated that the different concretes having the same slump may, indeed, have different workabilities under the site conditions. However, the slump test has been found to be useful in ensuring the uniformity among different batches of supposedly similar concrete under field conditions. The slump test is limited to concretes with maximum size of aggregate less than 38 mm.

The *VeBe test* [26 and 35] is suitable for stiff concrete mixes having low and very low workability. Compared to the slump test and compacting factor test, the VeBe test has the advantage that the concrete in the test receives a similar treatment as it would in actual practice. The test consists in moulding a fresh concrete cone in a cylindrical container mounted on a vibrating table. The concrete cone when subjected to vibration by starting the vibrator starts to occupy the cylindrical container by the way of getting remoulded. The remoulding is considered complete when the concrete surface becomes horizontal as indicated by the disappearance of the air bubble under the transparent follower disk. The time required for complete remoulding in seconds multiplied by the ratio of the final volume to the initial volume is considered as a measure of workability and is expressed as the number of VeBe seconds. Since the endpoint of the test when the concrete surface becomes horizontal is to be ascertained visually, it introduces a source of error which is more pronounced for concrete mixes of high workability and consequently records high VeBe time. For concrete of slump in excess of 125 mm, the remoulding is so quick that time cannot be measured. The test is therefore, not suitable for higher workability. An approximate relationship between slump and VeBe time is given in *Fig. 2.1.*

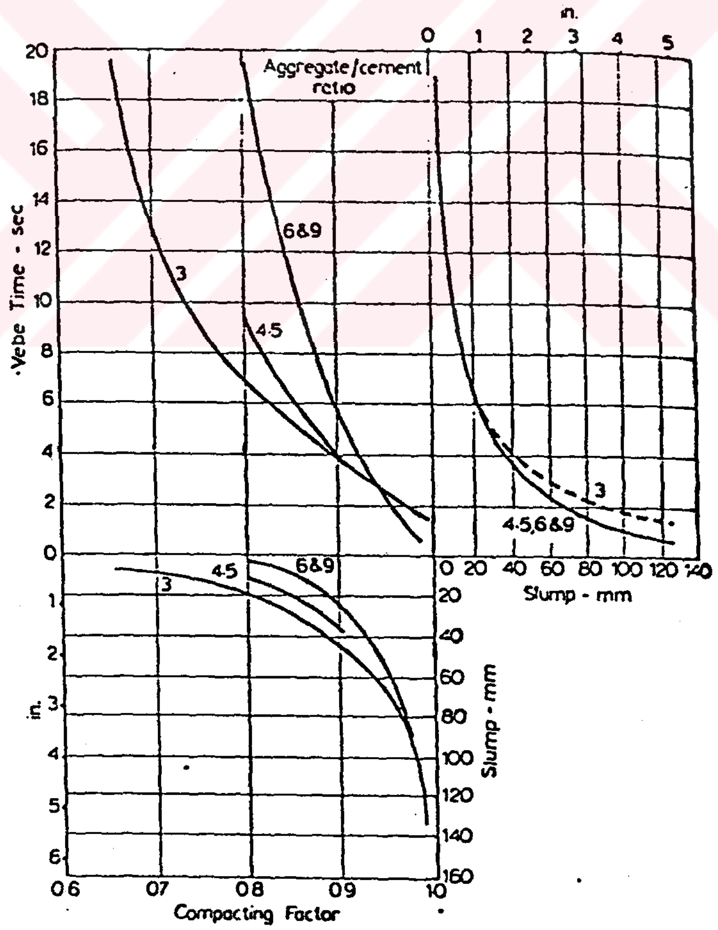


Fig 2.1 General Pattern of Relations between Workability Tests for Mixes of Varying Aggregate/Cement Ratios [1, p 220]

The *flow test* [36] gives the satisfactory performance for concretes of the consistencies for which slump test can be used. The test consists of moulding a fresh concrete cone on the top of the platform of flow table, and in giving 15 jolts of 12.5 mm magnitudes. The spread of the concrete, measured as the increase in diameter of concrete heap and expressed as the percentage of the original base diameter of cone, is taken as a measure of the *flow or consistency of the concrete*. The test suffers from the drawback that the concrete may scatter on the flow table with a tendency towards *segregation* [3, p 61].

Nasser's K-probe is inserted vertically to a certain depth into fresh concrete in the mould, either before or after compaction, and, following withdrawal of the probe after one minute, the residual height of the mortar in the tube is measured. The external diameter of the probe is 19 mm and it contains openings through which mortar enters the tube.

Nasser and Rezk claim that the test gives a measure of workability of the concrete because the probe reading is affected by cohesive, adhesive, and friction forces within the mix. Thus, an over-wet mix, which exhibits a high slump, would lead to a relatively low level of mortar retained in the probe, this being the result of segregation. Nevertheless, the probe reading appears to be related to slump, providing this does not exceed 80 mm [1, p 217].

2.2.3. Effect of Time and Temperature on Workability

Freshly mixed concrete stiffens with time. This should not be confused with setting of cement. It is simply that some water from the mix is absorbed by the aggregate, some is lost by evaporation, particularly if the concrete is exposed to sun or wind, and some is removed by the initial chemical reactions. The exact value of the loss in workability varies with the richness of the mix, the type of cement, the water/cement ratio, the temperature of the concrete, and the initial workability.

The workability of a mix is also affected by the ambient temperature. On a hot day the water content of the mix would have to be increased for a constant workability to be maintained. A decrease in workability is also observed at temperatures below 15°C.

Moreover, it seems that the loss of slump in hot and dry air is greater than the decrease in ease of placing. There is therefore no corresponding large increase in the water requirement. These findings apply up to 40°C and within 20 minutes of mixing. Over longer periods, there is an unmistakable loss of slump so that, for instance, with a long haul of ready-mixed concrete, high temperature would increase the water requirement for a given workability [1, p 221]. The related specifications has been discussed in *Section 2.2*.

3. PROPERTIES OF HARDENED CONCRETE

3.1. INTRODUCTION

The properties of fresh concrete are important only in the first few hours of its history and so far as they affect the properties of hardened concrete whereas the properties of hardened concrete assume an importance which is retained for the remainder of the service life of the concrete. The important properties of hardened concrete are strength, deformation under load, durability, permeability and shrinkage. In general, strength is considered to be the most important property and the quality of concrete is often judged by its strength. There are, however, many occasions when other properties are more important, for example, low permeability and low shrinkage are required for water-retaining structures. Although in most cases an improvement in strength results in an improvement of the other properties of concrete there are exceptions. For example, increasing the cement content of a mix improves strength and imperviousness in lean mixes but results in higher shrinkage which in extreme cases can adversely affect durability and permeability [6, p 150].

3.2. STRENGTH OF CONCRETE

Strength of concrete is commonly considered its most valuable property, although in many practical cases other characteristics, such as durability and impermeability, 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 hardened cement paste.

Three types of compression test specimens are used: cubes, cylinders, and prisms. The tendency nowadays especially in research, is to use cylinders in preference to cubes.

Cube Tests: The specimens are cast in steel or cast-iron moulds, generally 150 mm or 200 mm cube, which should conform to the cubical shape, prescribed dimensions and planeness within narrow tolerances. The mould and its base should be clamped together during casting to reduce leakage of cement paste. The use of rigidly connected base is essential when compaction is effected by means of vibration.

In the compression test, the cube is placed with the cast faces in contact with the platens of the testing machine, i.e. the position of the cube when tested is at right angles to that as-cast. The load on the cube should be applied at a constant rate of stress equal to 15 MPa/min [37, 38 and 39]. Because of the non-linearity of the stress-strain relation of concrete at high stresses, in a load controlled test, the rate of increase in strain must be increased progressively as failure is approached, i.e. the speed of the movement of the head of the testing machine has to be increased.

Cylinder Test: The standard cylinder is 150 mm in diameter, 300 mm long and is cast in a mould generally made of steel or cast iron, preferably with a clamped base. Non-reusable cardboard moulds are sometimes used, but they result in an apparent lowering of strength of the order of a few percent, possibly due to expansion of the mould during setting. The rate of loading specified in *TS 3114 and TS 3323* is 1.5-3.5 kPa/s in stress controlled test and 1.3 mm/min in strain controlled tests.

3.2.1. Effect of End Condition of Specimen and Capping

When tested in compression, the top surface of the test cylinder is brought into contact with the platen of the testing machine and, since this surface is not obtained by casting against a machined plane but finished by means of a float, the top surface is somewhat rough and not truly plane. Under such circumstances stress concentrations are introduced and the apparent strength of the concrete is greatly reduced. Lack of planeness of 0.25 mm can lower the strength by one-third. Convex end surfaces cause a greater reduction than concave ones as they generally lead to higher stress concentrations. The loss in strength is particularly high in high-strength concrete.

There are three means of overcoming the ill-effects of an uneven end surface of the specimen: capping, grinding, and packing with a bedding material.

Capping with a suitable material does not adversely affect strength and reduces its scatter compared with uncapped specimens. An ideal capping material should have strength and elastic properties similar to those of the concrete in the specimen; there is then no enhanced tendency to splitting, and a reasonably uniform distribution of stress over the cross-section of the specimen is achieved.

The capping operation may be performed either just before testing or alternatively soon after the specimen has been cast. Different materials are used in either case but, whatever the capping material, it is essential that the cap be thin, preferably 1.5 to 3 mm thick. The capping material must be no weaker than the concrete in the specimen but too great a difference in strength is thought undesirable since a very strong cap may produce a large lateral restraint and thus lead to an apparent increase in strength. The influence of the capping material on strength is much greater in the case of high- or medium-strength concrete than when low-strength concrete is used; in latter case, the capping material rarely cause a reduction in strength of more than *5 to 10 percent*.

3.2.2. Testing of Compression Specimens

In addition to being plane, the end surfaces of the cylinder should be normal to its axis, and this guarantees also that the end planes are parallel to one another. A small tolerance is permitted, as an inclination of the axis of the specimen to the axis of the testing machine of 6 mm in 300 mm has been found to cause no loss of strength. The axis of the specimen, when placed in the testing machine, should be as near the axis of the platen as possible, but errors up to 6 mm do not affect the strength. Likewise, a small lack of parallelism between the end surfaces of the specimen does not adversely affect its strength, provided the testing machine is equipped with a seating which can align freely, as prescribed by *BS 1881: Part 4:1970* and *TS 3114* [37].

3.2.3. Effect of Height/Diameter Ratio on Strength

Standard cylinders are of height h equal to twice the diameter d, but sometimes specimens of other proportions are encountered. This is particularly the case with cores cut from *in-situ* concrete.

For values of h/d smaller than 1.5 the measured strength increases rapidly owing to the restraining effect of the platens of the testing machine. When h/d varies between about 1.5 and 4, strength is affected only little, and for h/d values between 1.5 and 2.5 strength is within *5 percent* of the strength of standard specimens (*h/d=2*). For values of *h/d* above 5, strength falls off more rapidly, the effect of the slenderness ratio becoming apparent.

It seems thus that the choice of the standard *h/d* ratio of 2 is suitable, not only because the end effect is largely eliminated and a zone of uniaxial compression exists within the specimen, but also because a slight departure from this ratio does not seriously affect the measured value of strength.

3.2.4 Comparison of Strength of Cubes and Cylinders

According to BS 1881:Part 4: 1970 and TS 500, the strength of a cylinder is taken to be to four-fifths of the strength of a cube, but experiments have shown that there is no simple relation between the strengths of the specimens of the two shapes. The ratio $f_{cylinder}/f_{cube}$ depends primarily on the size or volume of the specimens and on the level of strength of the concrete, and is higher the higher (closer to unity) the strength of concrete.

It is difficult to say which type of specimen is better but there seems to be a tendency, at least for research purposes, to use cylinders rather than cubes, and this has been recommended by RILEM - an international organization of testing laboratories. Cylinders are believed to give a greater uniformity of results for nominally similar specimens as their failure is less affected by the end restraint of the specimen; their strength is less influenced by the properties of the coarse aggregate used in the mix; and the stress distribution on horizontal planes in a cylinder is more uniform than on a specimen of square cross-section.

3.2.5. Influence of Rate of Application of Load on Strength

In the range of speeds at which a load can be applied to a specimen, the rate of application has a considerable effect on the apparent strength of concrete: the lower the rate at which stress increases the lower the recorded strength. This is probably due to the increase in strain with time owing to creep, and when limiting strain is reached failure takes place largely independently of the value of the stress applied. Loading in compression over a period of *30 to 240 minutes* has been found to cause failure at *84 to 88 percent* of the ultimate strength obtained when the load is applied at the rate of approximately 12 MPa/min. Concrete can withstand indefinitely only stresses up to about *70 percent* of the strength determined under a load applied at the rate of *12 MPa/min.*

3.2.6. Influence of Moisture Condition during Test

The modulus of rupture of concrete which has been allowed to dry is lower than the modulus of a similar specimen in a saturated condition. This differences is due to the tensile stresses induced by restrained and non-uniform shrinkage prior to the application of the load. The magnitude of the apparent loss of strength depends on the rate at which moisture evaporates from the surface of the specimen.

If, however, the test specimen is small and drying takes place very slowly, so that internal stresses can be redistributed and alleviated by creep, an increase in strength is observed. Conversely, wetting of dry specimens prior to testing reduces their strength probably due to the differential swelling induced by the disjoining pressure of the water absorbed which may induce tensile stresses within the dry zones. However, interpretation of this phenomenon is still largely controversial.

The strength of compression test specimens also increases on drying. This is probably due to the fact that tensile stresses may develop in the lateral direction due to the pore pressure of the water in the voids.

3.2.7. Influence of Size of Specimens on Strength

Since concrete is composed of elements of variable strength it is reasonable to assume that the larger the volume of the concrete subjected to stress the more likely it is to contain an element of a given extreme (low) strength. As a result, the measured strength of a specimen decreases with increase in its size, and so does the variability in strength of nominally similar specimens. Since the influence of size on strength depends on the standard deviation of strength it follows that the size effects are smaller the greater the homogeneity of the concrete. [1, p 530]

3.2.8. Water/Cement Ratio

In engineering practice, the strength of concrete at a given age and cured at a prescribed temperature and humidity is known to depend primarily on two factors only: the water/cement ratio and the degree of compaction. The presence of voids in concrete greatly reduces its strength: *5* per cent of voids can lower strength by as much as *30* per cent and even *2* per cent voids can result in a drop of strength of more than *10* per cent, depending also on the pore size distribution and shape. But at this stage we shall consider practically *fully-compacted concrete* only: in practice this is taken to mean that the hardened concrete contains about *1 per cent of air voids* in the fresh state and apparent porosity does not exceed about 15%.

When concrete is fully compacted its strength is taken to be inversely proportional to the water/cement ratio. This relation was preceded by a "law" established by Duff Abrams. He found strength to be equal to

$$f_c = \frac{K_1}{K_2^{w/c}}$$

where w/c represents the water/cement ratio of the mix (originally taken by volume), and K_1 and K_2 are empirical constants.

Abrams' "law", although established independently, is similar to a general rule formulated by *Feret* in that they both relate strength of concrete to the volumes of water and cement. *Feret's rule* was in the form

$$f_c = K_F \left(\frac{c}{c+w+a} \right)^2$$

where f_c is the strength of concrete, c, w, and a are the absolute volumes of cement, water, and air (per unit volume of concrete), respectively, and K_F is a coefficient.

The water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. Thus the water/cement ratio and the degree of compaction both affect the volume of voids in concrete, and this is why the volume of air in concrete is included in Feret's expression.

This effect may also be taken into account by *Modified Graff* formulation:

$$f_c = \frac{f_{cc}}{K_{GM}}\left(\frac{C}{W+V_{air}}\right)^2$$

where C and W are cement and water contents in kg/m^3 concrete, V_{air} is volume of air and K_{GM} is a coefficient, f_{cc} is standard compressive strength of cement obtained by applying a standard specified test (*e.g. 37.2 MPa in this work*).

The influence of the volume of pores on strength can be expressed by a power function of the type

$$f_c = f_{c,0}(1-p)^n$$

where f_c = strength of concrete with porosity p

$f_{c,0}$ = strength at zero porosity

Also another strength formula was developed by *Bolomey*

$$f_c = K_{B1}\left(\frac{C}{W+d_W \cdot V_{air}} + K_{B2}\right)$$

where KB1, KB2 = Bolomey's function coefficients [1, p 268].

3.2.9. Effective Water in The Mix - Moisture Correction

We consider as effective that water which occupies space outside the aggregate particles when the gross volume of concrete becomes stabilized, i.e. approximately at the time of setting. Hence the terms ***effective*** or ***net*** water/cement ratio.

Generally, water in concrete consists of that added to the mix and that held by the aggregate at the time when it enters the mixer. A part of the latter water is absorbed within the pore structure of the aggregate, if the moisture content of aggregate is less than its water absorption, while some exists as free water on the surface of the aggregate and is therefore air-filled. Sometimes a part of the water added to the mix may be absorbed by the dry aggregate during the first half hour or so after mixing. Under such circumstances the demarcation between absorbed and free water is a little difficult unless the moisture content and absorption of aggregate is continuously monitored during production.

On a site, the aggregate is as a rule wet, and the water in excess of that required to bring it to a saturated and surface-dry condition is considered to be the *effective water of the mix*. The strength curves or tables in standards and specifications are based on the water in excess of that absorbed by aggregate. On the other hand, the aggregate is frequently in dry condition in the laboratory and therefore, the aggregate to be used in a trial batch should be brought to saturated and surface-dry condition by adding an adequate amount of water and allowing time for absorption. There is also the water loss during trial batch production in a laboratory which has a much higher surface to volume ratio. Moisture correction is therefore necessary in translating laboratory results into mix proportions to be used on a site throughout the production and all reference to water/cement ratio, and moisture content and absorption must make it clear if total rather than effective water is considered [1, p 279].

3.2.10. Influence of Aggregate on Strength

When concrete is stressed, failure may originate within the aggregate, the matrix or at the aggregate-matrix interface; or any combination of these may occur. In general the aggregate are much stronger than the cement paste, the mortar phase or the concrete itself and in such cases the variation in aggregate strength has little effect on the strength of concrete.

The bond between aggregate and cement paste matrix interface is an important factor determining concrete strength. Bond strength is influenced by the shape of the aggregate, its surface texture and cleanliness. A smooth rounded aggregate will result in a weaker bond between the aggregate and matrix than an angular or irregular aggregate or an aggregate with a rough surface texture. The associated loss in strength however may be offset by the smaller water-cement ratio required for the same workability. Aggregate shape and surface texture affect the tensile strength more than the compressive strength. A fine coating of impurities, such as silt and clay, on the aggregate surface hinders the development of a good bond. A weathered and decomposed layer on the aggregate can also result in a poor bond as this layer can readily become detached from the sound aggregate beneath.

The aggregate size also affects the strength. For given mix proportions, the concrete strength decreases as the maximum size of aggregate is increased. On the other hand, for a given cement content and workability this effect is opposed by a reduction in the water requirement for the larger aggregate. However, it is probable that beyond a certain size of aggregate there is no obvious advantage in further increasing the aggregate size except perhaps in some instances when larger aggregate may be more readily available or a larger maximum size is to be used to reduce cement content and temperature rise due to hydration of cement such as in the case of mass concrete [6, p 155]. The optimum maximum aggregate size for reinforced concrete structures is to be chosen taking into account the wall-effect. (*See section 6.2, page 75*).

3.2.11. Influence of Air Content on Strength

There are some further effects of air entrainment on the properties of concrete, some beneficial, others not.

One of the most important is the influence of voids on the strength of concrete at all ages. The strength of concrete is direct function of its density ratio, and voids caused by entrained air will affect the strength in the same way as voids of any other origin. *Fig 3.1* shows that when entrained air is added to a mix without any other change in the mix proportions being made, the decrease in the strength of concrete is proportional to the volume of air present. That the origin of the air is scientifically not significant is apparent from the dotted curve in *Fig 3.1* which shows the strength-void ratio relation for the case when the voids are due to inadequate compaction and not to entrainment. The range of test covered mixes with water/cement ratio between *0.45 and 0.72,* and this shows that the loss of strength expressed as a fraction of the strength of air-free concrete is independent of the mix proportions. The average loss of compressive strength is *5.5 %* for each per cent of air present. The effect on the modulus of rupture is much smaller.

It should be noted that strength is affected by the total volume of all the voids present: entrapped air, entrained air, capillary pores, and gel pores. When entrained air is present in a mix, the total volume of capillary pores is smaller because a part of the gross volume of cement paste consists of entrained air. This is

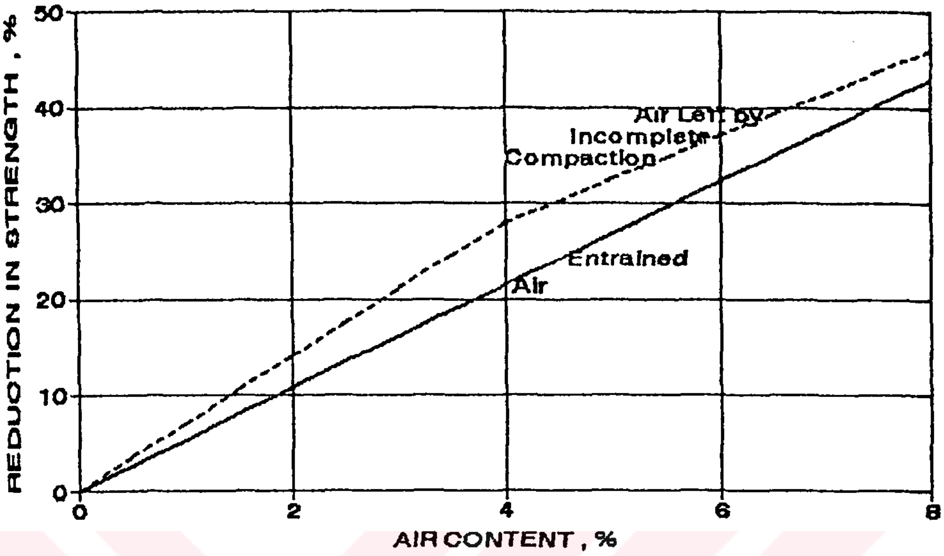


Fig. 3.1 Effect of Entrained Air and Accidental Air on the Strength of Concrete [1,p 483]

not a negligible factor because the volume of entrained air represents a significant proportion of the gross volume of the paste [1, p 483]. It should also be kept in mind that the size distribution and shape of the voids would also affect the reduction in strength.

3.3. DESTRUCTIVE TESTS

3.3.1. Compressive Strength Test

Of the various strengths of concrete the determination of compressive strength has received a large amount of attention because the concrete is primarily meant to withstand compressive stresses. Cubes, cylinders and prisms are the three types of compression test specimens used to determine the compressive strength. The cubes are usually of 100, 150 or 200 mm side, the cylinders are 150 mm diameter by 300 mm height. The specimens are cast, cured and tested as per standards prescribed for such tests. When cylinders are used, they have to be suitably capped before the test, an operation not required when other types of specimens are tested.

The compressive strengths given by different specimens for the same concrete mix are different. The cylinders and prisms of a ratio of height or length to the lateral dimension of 2 may give a strength of about *75 to 85* per cent of the cube strength of normal-strength concrete [3, p 79].

3.3.2. Splitting Tensile Test

In this test, a concrete cylinder, of the type used for compression tests, is placed with its axis horizontal between the platens of a testing machine, and the load is increased until failure by splitting along the vertical diameter takes place.

In practice narrow strips of a packing material, such as plywood, are interposed between the cylinder and the platens. Without packing strips, the recorded strength is lower, typically by about 8 per cent. These strips are usually 3 mm thick, and it is convenient to make their width equal to 1/12 of the diameter of the cylinder.

During the splitting test, the platens of the testing machine should not be allowed to rotate around an axis parallel to the axis of specimen, but should be permitted to rotate around an axis perpendicular to that of the specimen in order to accommodate a possible non-parallelism of the generatrices of the cylinder.

The splitting test is simple to perform and gives more uniform results than other tests, but splitting tensile strength is *5 to 12* per cent higher than the direct tensile strength. The reason for this lies partly in the fact that more than one single crack is formed in zones close to the packing strips which increases the energy consumed, and partly because a relatively much smaller volume of concrete is subjected to tensile stresses.

In this test, with normal aggregate, the presence of large particles near the surface to which the load is applied may influence the behaviour [1, p 549].

3.3.3. Flexural Strength Test

The determination of flexural tensile strength is essential to estimate load at which the concrete members may crack. As it is difficult to determine the tensile strength of concrete by conducting a direct tension test, it is computed by flexure testing. The flexural tensile strength at failure or the modulus of rupture is thus determined and used when necessary. It is critically important in the design of pavement slabs and airport runways as flexural tension is critical in these cases. The modulus of rupture is determined by testing standard test specimens of 150 mm x 150 mm x 750 mm over a span of 600 mm or 100 mm x 100 mm x 500 mm over a span of 400 mm, under symmetrical two-point loading. The modulus of rupture is determined from the moment at failure M, by $f_r=M/W_s$ where W_s is the section modulus. Thus computation of f_r assumes a linear elastic behaviour of the material in both the tension and compression zones up to failure, which is only a rough estimation. The results are affected by the size of the specimens; casting, curing and moisture conditions; manner of loading (third point or central point loading); rate of loading, etc. The test is conducted and the strength determined according to prescribed standards. The strength estimated by flexure test is higher than the direct tensile strength of concrete due to the assumption of the linear behaviour of material up to failure in the computation of f_r. On the other hand, the direct test gives lower apparent tensile strength. The accidental eccentricity in the direct tension test may also lower the apparent tensile strength. Another reason for the difference is the volume of concrete subjected to tension in third point flexural loading is less than about *1/2* of that in direct tension when the tests are carried out on identical specimens [3, p 79].

3.3.4. Relation Between Compressive and Tensile Strengths

From the discussion on the strength of compression and tension (both direct and flexure) test specimens it would be expected that the two types of strength are closely related. This is indeed the case but there is no direct proportionality, the ratio of the two strengths depending on the general level of strength of the concrete. In other words, as the compressive strength, f_c increases, the tensile strength, f_t, also increases but at a decreasing rate.

A number of factors affects the relation between the two strengths. The beneficial effect of crushed coarse aggregate on flexural strength is known [1, p 287], but it seems that the properties of fine aggregate also influence the f_t/f_c ratio. The ratio is furthermore affected by the grading of the aggregate. This is probably due to the different magnitude of the wall effect and stress concentration in beams and in compression specimens: their surface/volume ratios are dissimilar so that different quantities of mortar are required for full compaction.

Age is also a factor in the relation between f_t and f_c: beyond about one month the tensile strength increases more slowly than the compressive strength so that the ratio f_t/f_c decreases with an increase in f_c.

The tensile strength of concrete is more sensitive to inadequate curing than the compressive strength, possibly because the effects of non-uniform shrinkage of flexure test beams are very serious in generating laws in the form of cracks and/or increasing the crack lengths . Thus air-cured concrete has a lower f_t/f_c ratio than concrete cured in water and tested wet.

Air entrainment affects the f_t/f_c ratio because the presence of air lowers the compressive strength of concrete more than the tensile strength, particularly in the case of rich and strong mixes. The influence of incomplete compaction is similar to that of entrained air.

This is probably due to the fact that the thin cracks governing the tensile strength are present independent of the air content, whereas an increase in entrained air causes a reduction in compressive strength by lowering the net solid cross-sectional area. Under compression, the thin cracks perpendicular to the direction of loading close and do not cause a reduction in compressive strength while the macropores due to entrained air act to reduce the cross-section carrying compressive loads.

A number of empirical formulae connecting f_t and f_c have been suggested, many of them of the type

$$f_t = k\ (f_c)^n$$

where k and n are coefficients.

Committéé Européen du Béton assumes that the mean direct tensile strength is related to the *characteristic* compressive strength of cylinders by the expression

$$f_t = 0.30\ (f_{cyl,k})^{\frac{2}{3}}$$

the strengths being expressed in MPa. Such a relation may be of use in design but does not properly describe the properties of the material. Another formula was suggested at University of Illinois

$$f_t = \frac{3000}{4+\dfrac{12000}{f_{cyl}}}$$

where f_t is the modulus of rupture and f_{cyl} is determined on standard test cylinders, both expressed in pounds per square inch [1, p 301].

3.4. EFFECTS OF WATER-REDUCING ADMIXTURES ON THE PROPERTIES OF HARDENED CONCRETE

The major physical attributes of concrete as a construction material are a high compressive strength and stiffness, an ability to protect and restrain steel and, most important of all, to retain these properties over a considerable period of time. The effect that water-reducing admixtures have on these properties can be considered from the point of view of design parameters, i.e. those properties of concrete at a relatively early age (usually 28 days) which are used for load calculations, and longer term aspects or durability.

The three most important properties of concrete used in calculations for load-bearing applications are compressive strength, the tensile strength and the modulus of elasticity. However, for certain applications, e.g. water-retaining structures, the permeability or porosity of concrete will be a relevant design criterion.

a) Effect of WRA on Compressive strength

The compressive strength at 28 days of concrete containing water-reducing admixtures of the lignosulphonate, hyroxycarboxylic acid, melamine formaldehyde sulphonate and naphthalene formaldehyde sulphonate types is a function of the water/cement ratio in the manner of concrete or cement paste which does not contain an admixture. It is often claimed that materials of these types produce higher 28-day compressive strength for a *given* water/cement ratio, and this is one of the findings in the present work. However, there are research results which do not corroborate an increase in strength above that which could be accounted for by a decrease in W/C ratio. Typical data for British cements and aggregates are shown in *Figs. 3.2* and *3.3, which* span a

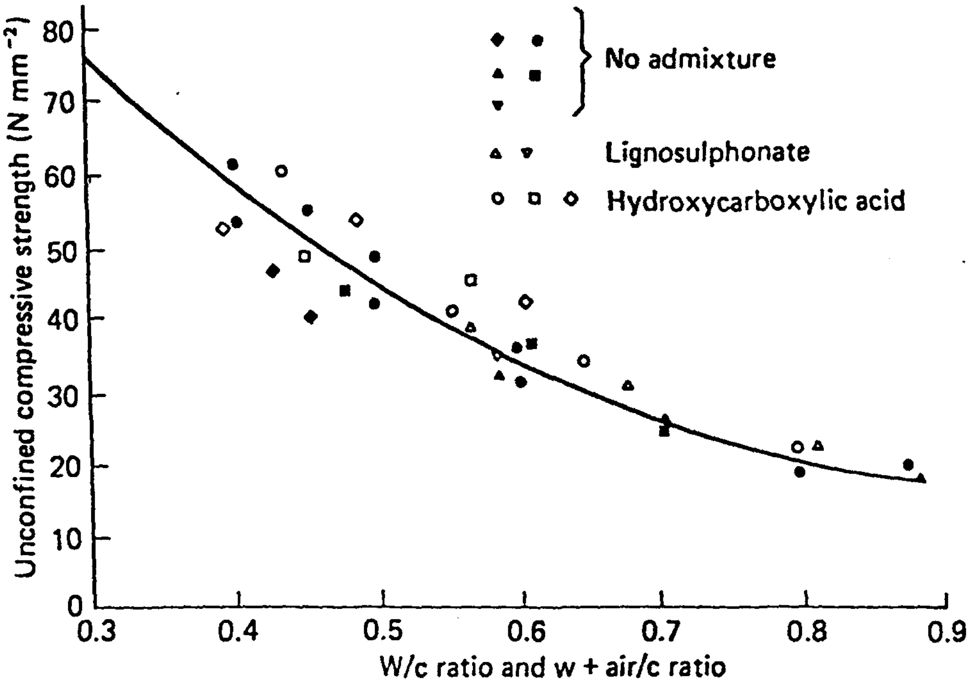


Fig. 3.2 The Relationship Between W/C Ratio (Water and Air-Cement Ratio) and Compressive Strength of Concrete Containing Lignosulphonate and Hydroxycarboxylic Acid Based Water-Reducing Agents [2, p 58]

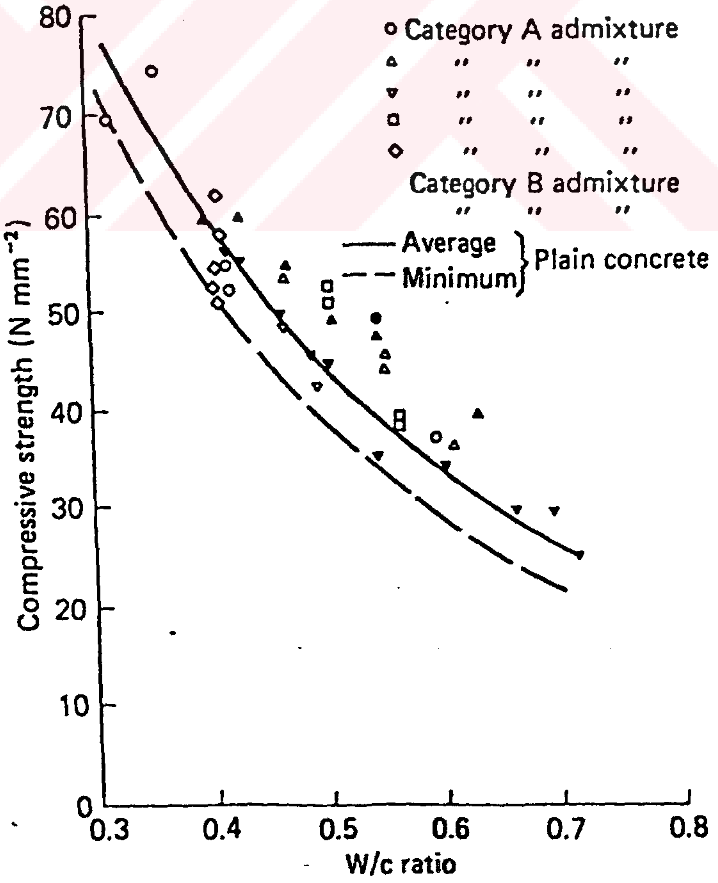


Fig. 3.3 The Relationship Between W/C Ratio and Compressive Strength of Concretes Containing Superplasticizers [2, p 58]

range of aggregate and mix design types for lignosulphonates, hyroxycarboxylic acid water-reducing agents, melamine formaldehyde and naphthalene formaldehyde sulphonate superplasticizers.Therefore, for materials of these types, no special consideration has to be taken into account for design purposes as far as 28-day compressive strength is concerned since, in general, the increase does not seem to be sufficiently significant. Nevertheless, an increase of around 5 MPa is apparent especially in *Fig. 3.3* for W/C ratios of *0.40-0.60.*

In an overall evaluation, it can be stated that air-entraining water-reducing admixtures require special consideration; the presence of entrained air leads to a reduction in compressive strength, whilst the water reduction and better dispersion and homogeneity results in a compensatory increase in strength. The effect can be quantified, however, by considering the amount of entrained air in terms of an equivalent volume of water to calculate the (air and water): cement ratio. This new factor can be used to estimate the expected strength from *Fig. 3.2*

b) Effect of WRA on Tensile strength

The tensile strength can be measured in two ways: *(i)* direct tensile strength from "dumbbell" specimens;

(ii) splitting tensile strength from cylinders. Alternatively the flexural strength can be measured using rectangular prisms. Methods *(i)* and *(ii)* give similar values, whilst flexural strength, [2, p 59] gives somewhat higher values.

Only limited data are available to illustrate the effects of water-reducing admixtures on the relationship between compressive strength and tensile strength. However, *Table 3.1* summarizes the tensile, flexural and compressive strengths for some published results and also includes some comparative figures for control concretes.

It can be concluded that water-reducing admixtures of the lignosulphonate and hydroxycarboxylic acid types will not significantly alter the relationship between the compressive strength and the tensile and flexural strengths in normal strength concretes.

Table 3.1 Relationship Between the Compressive Strength and the Tensile and Flexural Strengths [2, p 60]

Admixture type	% of compressive strength		Average	
	Flexural	Tensile	Flexural	Tensile
Hydroxycarboxylic acid	—	6.9	15.2%	8.1%
	—	9.3		
	14.7	—		
	14.6	—		
	17.8	—		
	15.7	—		
	13.4	—		
None	—	6.3	16.2%	8.8%
	—	8.9		
	15.1	—		
	13.8	—		
	16.0	—		
	16.8	10.7		
	18.2	8.5		
	17.0	7.6		
		10.6		
Lignosulphonate		7.1	14.9%	7.5%
		7.8		
	15.2			
	16.3			
	13.2			

c) Effect of WRA on Modulus of elasticity

There is a paucity of recorded comparative data on the elastic modulus of concretes containing water-reducing admixtures. The one investigation of significance studied a lignosulphonate based material in corresponding mixes using five different cements and the results are given in *Table 3.2* as a ratio of the admixture-containing mix to the non-admixture containing mix of similar workability and 28-day compressive strength parameters.

Table 3.2 Elastic Modulus of Concrete Containing a Lignosulphonate Based Water-Reducing Agent as a Ratio of a Plain Mix [2, p 61]

Age (days)	Ratio of dynamic modulus Cement					Average
	1	2	3	4	5	
1	1.05	1.10	1.00	1.05	1.25	1.10
3	1.15	1.10	1.05	1.00	1.15	1.10
7	1.15	1.10	1.05	1.05	1.10	1.10
14	1.05	—	1.05	1.05	1.05	1.05
21	1.05	1.05	1.00	1.00	1.00	1.00
28	1.05	1.00	1.05	1.05	1.00	1.05
35	1.05	1.00	1.05	1.05	1.00	1.05
63	1.00	1.00	1.05	1.05	1.00	1.00
91	1.00	1.00	1.05	1.05	1.00	1.00
119	1.05	1.00	1.00	1.00	1.00	1.00
147	1.05	1.00	1.05	1.05	1.00	1.05
182	1.00	1.00	1.00	1.00	1.00	1.00

There are strong indications that after 28 to 35 days curing, there is little or no difference in the modulus of elasticity between the corresponding mixes, and at earlier ages the trend is towards a higher modulus.

More recent work on a hydroxycarboxylic acid based material revealed the data given in *Table 3.3*

Table 3.3 Elastic Modulus of Concretes Containing a Hydroxycarboxylic Acid Water-Reducing Agent [2, p 62]

Concrete mix number	Aggregate type	W/c ratio	Admixture	28-day strength (N mm^{-2})	Modulus of elasticity at 28 days (N mm^{-2})
1.1	Quartz	0.65	No	30.0	29.6
1.2		0.65	Yes	29.3	29.2
1.3		0.60	Yes	41.8	30.5
2.1		0.45	No	38.2	33.8
2.2		0.45	Yes	40.6	35.2
2.3		0.40	Yes	46.5	39.2
3.1	Limestone	0.65	No	29.2	30.5
3.2		0.65	Yes	26.7	32.9
3.3		0.58	Yes	41.2	35.9
4.1		0.43	No	47.3	40.5
4.2		0.43	Yes	46.9	37.2
4.3		0.38	Yes	52.1	42.1

Some data have been compiled on concretes containing superplasticizers of the melamine formaldehyde and naphthalene formaldehyde types and *Fig. 3.4* illustrates that there is no apparent difference between concretes containing the superplasticizers and control concretes containing no admixtures [2, p 57].

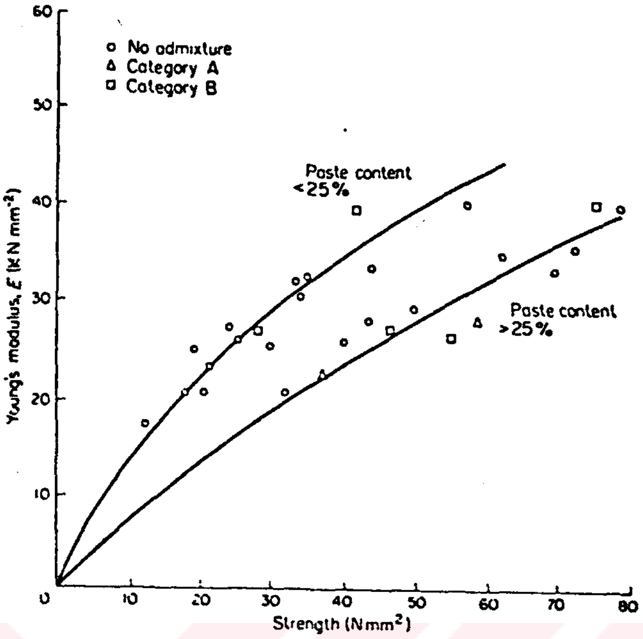


Fig. 3.4 The Effect of Superplasticizers on the Modulus of Elasticity [2, p 62]

3.5. NON-DESTRUCTIVE TESTS

The difficulties of core cutting, and indeed the entire procedure of making, curing and testing of standard test specimens would all be avoided, if concrete could be tested *in situ* in a manner harmless to the part tested. Various attempts to devise non-destructive tests have been made but few have been highly successful. In this work, Rebound Hammer Test and Ultrasonic Pulse Velocity tests were used.

3.5.1. Rebound Hammer Test

Various attempts to devise non-destructive tests have been made but few have been highly successful. One method that has found practical application within a limited scope is the rebound hammer test, devised by Ernst Schmidt. It is also known as the impact hammer, or sclerometer, test.

The test is based on the principle that rebound of an elastic mass depends on the hardness of the surface against which the mass impinges.

The test is sensitive to local variations in the concrete; for instance, the presence of a large piece of aggregate immediately underneath the plunger would result in an abnormally high rebound number; conversely, the presence of a void in a similar position would lead to a very low result.

The plunger must always be normal to the surface of the concrete under test, but the position of the hammer relative to the vertical will affect the rebound number. This is due to the action of gravity on the travel of the mass in the hammer.

The test determines in reality the hardness of the concrete surface and, although there is no unique relation between hardness and strength of concrete, empirical relationships can be determined for similar concretes cured in such a manner that both the surface tested by the hammer and the central regions have the same strength.

The test is of a comparative nature only, and the claims of the manufacturers that the rebound number can be directly converted into a value of compressive strength are not justified. In particular, the hardness of concrete depends on the elastic properties of the aggregate used, and may also be affected by large differences in mix proportions and by carbonation. Beyond the age of *90 days*, estimation of strength even for comparative purposes is not allowed in some standards (e.g., DIN 1045). Nevertheless, the test is useful as a measure of uniformity of concrete and is of great value in checking the quality of material throughout a structure, or in the manufacture of a number of similar products [1, p 573].

3.5.2. Ultrasonic Pulse Velocity

The standard tests of strengths of concrete are made on specially prepared specimens, which perforce are not true samples of the concrete in the actual structure. One result of this is that the degree of compaction of the concrete in the structure is not reflected in the results of the strength test, and it is not possible to determine whether the potential strength of the mix.

For these reasons, attempts have been made to measure in a nondestructive manner some physical property of concrete related to its strength. A considerable degree of success has been achieved in the determination of the longitudinal wave velocity in concrete. There is no unique relationship between this velocity and the strength of concrete but under specified conditions the two quantities are directly related. The common factor is the density of concrete: a change in the density results in a change in the pulse velocity. Likewise, for a given mix, the ratio of the actual density to the potential (fully compacted) density and the resulting strength are closely related. Thus the lowering of density caused by an increase in the water/cement ratio decreases both the compressive strength of the concrete and the velocity of a pulse transmitted through it.

The wave velocity is not determined direct but is calculated from the time taken by a pulse to travel a measured distance. This ultrasonic pulse - hence the name of the method of measurement - is obtained by applying a rapid change of potential from a transmitter driver to a piezo-electric crystal transducer in contact with one face of the specimen, emitting short trains of vibrations at its fundamental frequency. The receiver transducer is in contact with the. opposite face of the specimen under test. The receiver transducer in its turn generates an electrical signal, which is fed through an amplifier to a plate of a cathode-ray tube or counter circuit. A second plate supplies timing marks or signals at fixed intervals.

The ultrasonic pulse velocity technique is used as means of quality control of products which are supposed to be made of similar concrete: both lack of compaction and a change in the water/cement ratio would be easily detected. The technique can not, however, be employed for the determination of strength of concretes made of different materials in unknown proportions. It is true that there is a broad tendency for concrete of higher density to have a higher strength so that a general classification of the quality of concrete on the basis of the pulse velocity is possible.

In addition to this the ultrasonic pulse measurements can be used to detect the development of cracks in structures such as dams, and to check deterioration due to frost or chemical action. These are important applications of the technique, which is suitable for the detection of any development of voids in concrete.

Table 3.4 Classification of the Quality of Concrete on the Basis of Pulse Velocity [1, p 583]

Longitudinal pulse velocity km/s	Quality of Concrete
> 4.5	Excellent
3.5–4.5	Good
3.0–3.5	Doubtful
2.0–3.0	Poor
< 2.0	Very Poor

3.5.3. Combined Non-Destructive Tests

The various non-destructive test methods have been discussed individually but it is obviously possible to use more than one method at a time. This is advantageous when a variation in properties of concrete affects the test results in opposite directions. Such is the case, for instance, with the presence of moisture in concrete: an increase in the moisture content increase the ultrasonic pulse velocity but decreases the rebound number recorded by the Schmidt hammer [1, p 581]. It has been shown that better correlations exist between the strength of concrete and rebound number and pulse velocity than with either one of the latter two alone [29].

4. SUPERPLASTICIZERS

4.1. APPLICATIONS OF SUPERPLASTICIZER

4.1.1. Superplasticizers in Ready-Mixed Concrete

In general, most of the ready-mixed concrete in North America and Europe contains an admixture, the combined use of water-reducing and air-entraining agents is common. In Europe the use of air-entraining agents is less frequent. The ready-mixed concrete producer in both continents usually supplies concrete containing admixtures either on request from the client to provide a specific material or as a means of providing a specific type of concrete. However, in Turkey the client has to administer the whole process of using an admixture.

Although the use of admixture by the ready-mixed sector of the industry is generally similar to that of site batched concrete, there are several unique elements and problems in control: in situations where concrete is specified by compressive strength and workability, normal and retarding water-reducing admixtures are widely used as a means of attaining the required properties at lower cement contents, reducing variation in concrete properties in both the plastic and hardened state from batch to batch is of considerable importance in minimizing rejection levels in field batches.

Table 4.1 represents a comparison of the results obtained from concrete batches produced on the same plant with and without admixtures. The table summarizes data collected over a six-month period for two concretes of differing slump values (50 mm and 70 mm). It can be seen that the hydroxycarboxylic acid based normal water-reducing admixture produced no effect on the standard deviation for the 50 mm slump mixes, whilst an increase is noted for the higher workability mixes.

Table 4.1 Changes in Standard Deviations of a Ready-Mix Concrete Plant Using a Hydroxycarboxylic Water-Reducing Agent [2, p 196]

Slump	Admixture	No. of results	28-day fc (N/mm2)	S.Dev. (N/mm2)	Coeff of Var. %
75	No	59	46.0	4.3	9.3
75	Yes	61	52.0	5.8	11.2
50	No	386	44.0	5.0	11.4
50	Yes	43	48.0	4.9	10.2

The effect produced by the incorporation of a lignosulphonate based water-reducing agent is shown in *Table 4.2* Since the standard deviation of this particular plant was 5.0 MPa for mixes produced without the use of admixtures, it is evident that the use of admixture resulted in reduced variability.

These results indicate that in high workability mixes with cement contents in the median range, the admixture may cause an increase in the standard deviation. Thus in re-designing the mix to have a lower cement content in this class of concrete, adequate consideration should be given to this difference in standard deviation. Increased uniformity can be attained in this instance if the increase in standard deviation is compensated for by not utilizing the full potential cement reductions indicated by the mean 28-day strength.

Table 4.2 7-day and 28-day Strengths and Standard Deviations for Concrete Containing a Lignosulphonate Water Reducing Agent [2, p 196]

No. of (N/mm2) Mixes	Mean strength (N/mm2)		Standard Dev.	
	7 day	28 day	7 day	28 day
53	55.4	66.4	4.6	4.2

The coefficient of variation of 13.7% indicates an operation with a fair degree of control standard. However, these were random strength tests. The results represent concrete mixes where there was wide variation in slump, sand gradation, moisture content, mixing time and where a high coefficient of variation (*20%*) is usually anticipated. The significant difference between this and the usual concrete delivered to the small consumer is that a water-reducing admixture was used throughout.

Another example of the effect produced by admixtures in ready-mixed concrete is that a change in slump from 75 to 175 mm without a water-reducing admixture required an increase in water/cement ratio of 0.08. With the admixture the same variation in slump required an increase in water/cement ratio of only 0.05, indicating that such concretes permitted variations in slump with less increase in water demand and water-cement ratio [2, p 195].

4.1.2. Superplasticizers in High Strength Concrete

Aggregate-cement bond and matrix strength play a significant role in determining the strength of high strength concrete. The high cement contents that are generally required for such mixes are often counter-productive. High shrinkage stresses produced cause loss of aggregate-cement bond or cracking of the cement paste due to the restraint induced by the aggregate particles. Matrix strength is primarily dependent on matrix porosity, which is governed by the water-cement ratio.

The increased plasticity and reduced water and cement contents required to achieve high strength can be attained using normal and retarding water-reducing or superplasticizing admixtures. In general, water-reducing retarders are more effective in such mixes than normal water reducers.

Depending on the type of admixtures used, two approaches are feasible:

Method A: Using a normal or retarding water reducer, the water-cement ratio is reduced 6-10% at the same cement content and slump.

Method B: Using a superplasticizer, a concrete of lower water-cement ratio is produced at a lower cement content with the same increased workability [2, p 198].

4.1.3. Superplasticizers in Pumped Concrete

Chemical admixtures broaden the envelope of aggregate gradations which may be used in the mix, enable concrete to be placed under a wider range of job conditions, and enhance the physical properties while making the mix more pumpable.

Three broad classes of pumpable concrete usually used are:

(a) Low cement content mixes (210 kg/m^3)

(b) Medium cement content mixes (200-300 kg/m^3)

(c) High cement content mixes (>300 kg/m^3).

Mixes in both low and high cement content classes are more prone to problems than the medium range. In low cement content mixes poor cohesion results in segregation and in high cement content mixes thixotropy causes pipeline friction. Admixture will modify the flow characteristics of the paste, helping to achieve and maintain optimum flow characteristics.

For low cement content mixes, the admixture imparts water retentivity to the cement paste under forces tending to separate the mix water. (Special admixtures such as colloidally dispersed bentonite clay are available for assisting pumping of low cement content mixes).

Concretes in the medium range, although having satisfactory paste flow properties, often run into problems due to a lack of supply of consistent quality aggregates. Common problems are decreased cohesion of the cement pastes for mixes in the lower cement content range and increased friction to flow in mixes in the higher cement content range. In both instances the use of either normal or retarding water reducers in combination with an air-entraining agent will alleviate these problems. Air entrainment increase the cohesion of the cement paste, while the retarding water reducers enables the release of water to reduce the friction that develops in a thixotropic paste.

Mixes of high cement content tend to have thixotropic pastes. Consequently, flow through the aggregate-void channels is inhibited and the mobility of the peripheral grout layer decreases. Admixtures used in this class of concrete are of the dispersing agent type which induce lubrication by an increase in the free water content of the mix. Commonly used materials are calcium lignosulphonates and sodium salts of hydroxycarboxylic acid.

Pumped concrete must not only meet specified job performance criteria but should also remain stable under bvfa variety of job conditions, particularly in hot and cold weather. It is, therefore, common to find that concrete to be pumped will often contain two or more types of admixtures.

Pumping of lightweight concrete is another area where admixtures play a significant role in improving pumping characteristics. Such concretes are inherently more susceptible to segregation and absorption of water under pressure than normal concretes. The use of admixtures (air-entraining agent, superplasticizer or thickener) imparts increased viscosity and plasticity to the mix resulting in improved pumpability [2, p 213].

4.1.4. Superplasticizers in Flowing Concrete

Such concretes usually posses high consistencies with slump values in excess of 180 mm and flow table spread greater than 50 cm. The high workability is usually achieved by addition of superplasticizer to a 50-75 mm slump.

Due to the fluid-like character of flowing concrete mixes, there is a tendency for increased bleeding and segregation when normal mixes with slumps in the range of 75-100 mm are raised to values in excess of 180 mm. Therefore, some alteration to mix design is required to maintain adequate cohesion of mix. Aspects to be considered in the design of such mixes are:

(a) Cement type and content

(b) Fines content of the mix

(c) Aggregate properties

(d) Maximum placing slump

(e) Dosage of the admixture (as determined by admixture type, cement type, concrete temperature and initial slump)

(f) Sequence of addition.

Cement types IV and V are reported to require lower admixture dosage than types I and II to produce a given slump. The fineness of the cement may influence both the degree of slump increase and the strength levels attained. Finely ground cements require higher water contents or increased dosage to reach the desired high workability. The optimum cement contents which provide flowing concrete have been found to be in the range of 270-375 kg/m^3

Coarse aggregate characteristics such as shape and texture should be considered. Mixes containing crushed or angular aggregates will require a higher proportion of fines. A decrease in maximum aggregate size will usually promote flowing character.

The use of concretes with slump > 220 mm or flow table spread > 60 cm is not recommended since these mixes are prone to bleeding and segregation, particularly under vibration or when conveyor belts are used to transport the concrete.

Due to the varying solids content and, hence, the effective ingredient concentration in the various commercially available superplasticizers, particular attention should be paid to the manufacturer's recommended dosage for flowing concrete.

Factors which affect the dosage rate are concrete temperature, initial slump (i.e. slump before the addition of the superplasticizer), cement type and content, the presence of other conventional admixtures in the mix prior to the mix.

High concrete temperature, finely ground cement, high cement content (> 415 kg/m^3) and low initial slumps will require higher admixture dosages than the manufacturer's standard recommended dosage.

The presence of air-entraining agent, retarder or water reducer in the mix will produce a higher than anticipated slump increase. Consequently, bleeding and segregation may occur due to the cumulative dispersing action of the two admixtures. This behaviour is more prone in mixes with lower cement and fines contents. Control of all these variables ensures that consecutive loads are similiar in their placing and handling characteristics.

Flowing concrete has revolutionized concrete pumping techniques. High workability and concomitant cohesion achieved through the use of superplasticizers enables concrete to be placed farther, at faster rates and lower pumpline pressures [2, p 218].

4.2. EFFECT OF SUPERPLASTICIZER ON WORKABILITY

When a normal, accelerating, or retarding water-reducing admixture is utilized to increase the workability of a concrete mix by direct addition, it would be reasonable to assume that the extent of the effect would be markedly affected by changes in mix design parameters such as cement content, aggregate size, shape and grading, and the water-cement ratio. A study of many results indicates that this is not the case and *Fig.4.1* illustrates the relationship between initial and final slump for water-reducing admixtures at normal dosage levels. The hydroxycarboxylic acid type appears to be generally superior to the lignosulphonates in increasing the value of slump, and this difference is maintained over the initial slump of 0 to 100 mm. This non-dependence of mix design parameters on the effect of water-reducing admixture is perhaps less surprising when it is considered that factors such as wetting and adsorption of aggregates, attrition between aggregate particles, and sufficient excess water to achieve the required slump, have already been taken into consideration during the developments of the initial mix design to produce the relevant workability. Therefore the effect of water-reducing admixtures is above and beyond these requirements and leads to approximately the same increase in slump across the initial slump range.

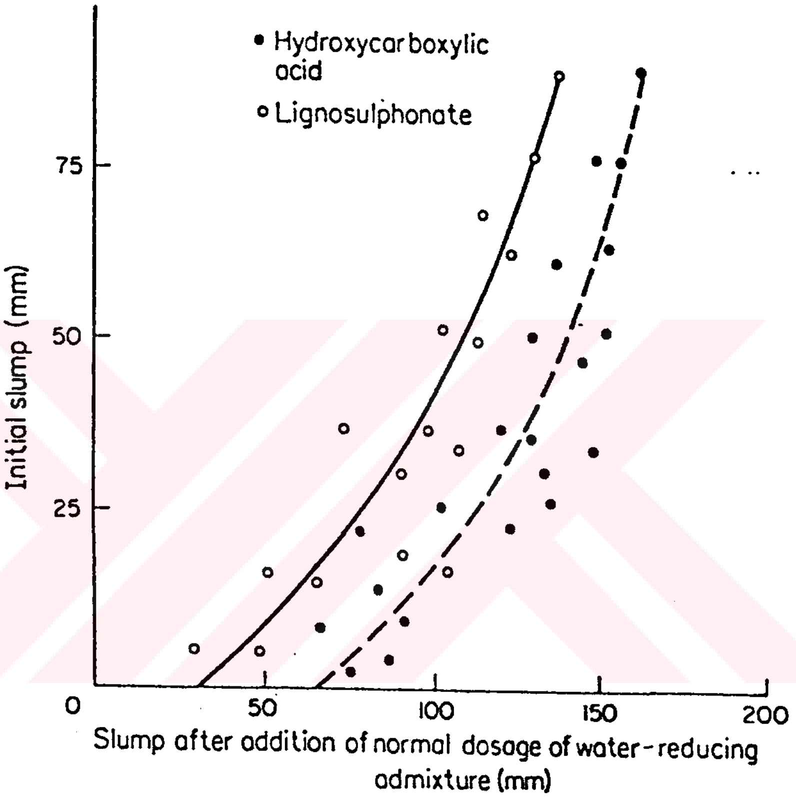


Fig. 4.1 The Relationship Between Initial Slump and the Slump After the Addition of Water-Reducing Admixtures [2, p 36]

This independence of efficiency in relation to mix design parameters is only true with regard to workability increases; where a concurrent change in water/cement ratio is made, a number of variables must be considered and will be discussed later.

The increase in workability obtained is, of course, a function of the dosage of admixture used and this is illustrated in *Fig. 4.2*. It will be appreciated that considerable retardation would be obtained at the higher dosage levels.

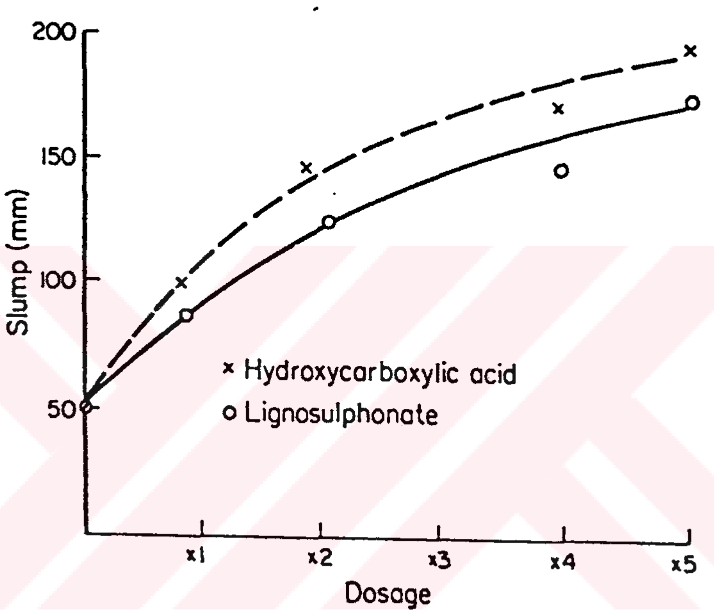


Fig. 4.2 The Effect on Slump of Varying Addition Levels of Water-Reducing Admixtures [2, p 37]

Superplasticizers operate in the same way as normal water-reducing admixtures, but because of the higher dosage used, the increase in workability is more dramatic. In addition, of course, the chemical materials used in their formulation do not significantly affect the setting or hardening rate of the concrete. Extreme workability produced by the addition of a superplasticizer requires a test other than slump or

VeBe, and the test utilized is a slightly modified form of the German DIN 1048 standard called the "flow table test". This is recorded in cm spread of a cone of concrete compacted under standard conditions. A relationship between slump and the flow table spread is shown in *Fig.4.3* and it can be seen that at the high slump values, the normal standard Abram's cone slump would not be sensitive enough.

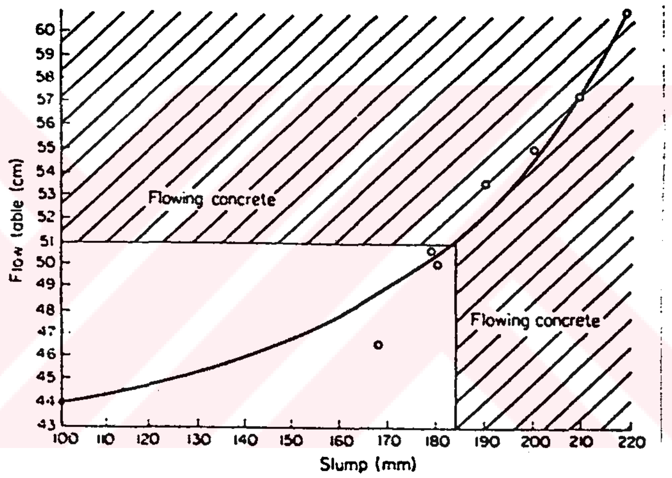


Fig. 4.3 The Relationship Between Slump and Flow Table Spread of Concrete Containing a Superplasticizer [2,p 38]

The workability of superplasticized concrete is dosage dependent, and typical results are shown in *Fig. 4.4*. The required dosage to obtain good cohesive flowing concrete of the required workability can be related to the initial slump prior to addition and, for a typical mix, results are shown in *Fig. 4.5* This indicates that either the initial slump or the addition level can be used as variables to give flowing concrete conforming to

DIN 1048 specification.

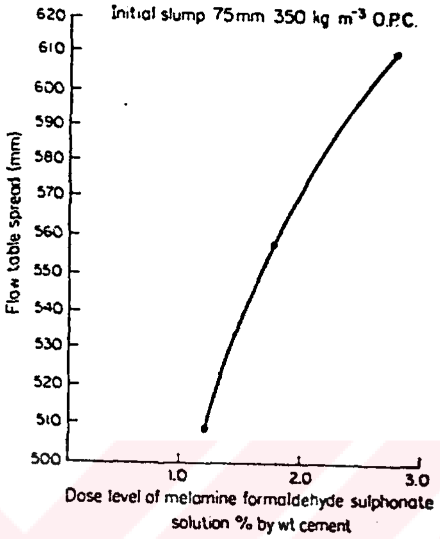


Fig. 4.4 The Effect on the Flow Table Spread of Various Addition Levels of a Superplasticizer [2, p 38]

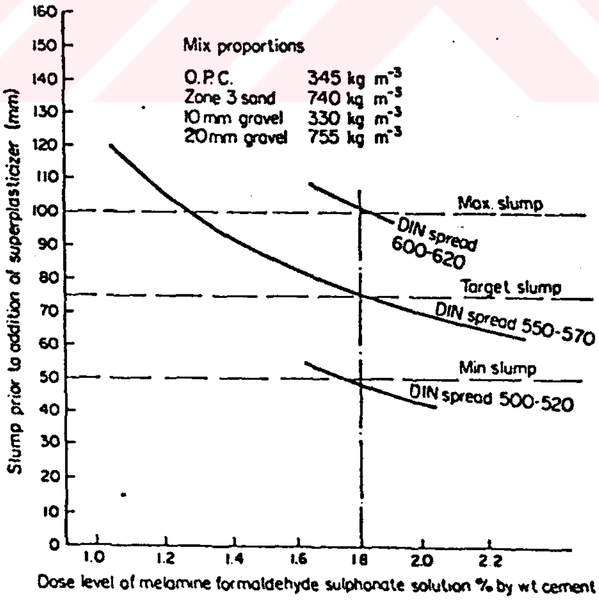


Fig. 4.5 The Relationship Between Initial Slump, the Flow Table Spread and the Addition of a SP [2, p 39]

Workability loss

Concrete is judged for its suitability and quality for a given set of mix proportions by its workability, usually in terms of the slump. Once the required workability of the concrete has been attained there will be progressive loss of workability with times as the hydration process proceeds. This process continue through the mixing, discharging, handling, placing and compaction by vibrating and any changes in the rate at which workability is lost can affect any or all of these steps. The loss of workability generally appears to be more pronounced with mixes containing water-reducing admixture and is illustrated in *Fig 4.6.* An increase in the dosage apparently reduces the slump loss as shown in *Fig 4.7*

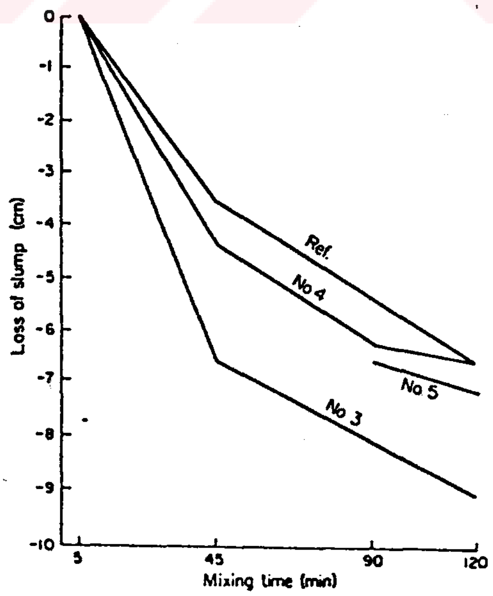


Fig. 4.6 The Loss of Slump With Time [2, p 41]

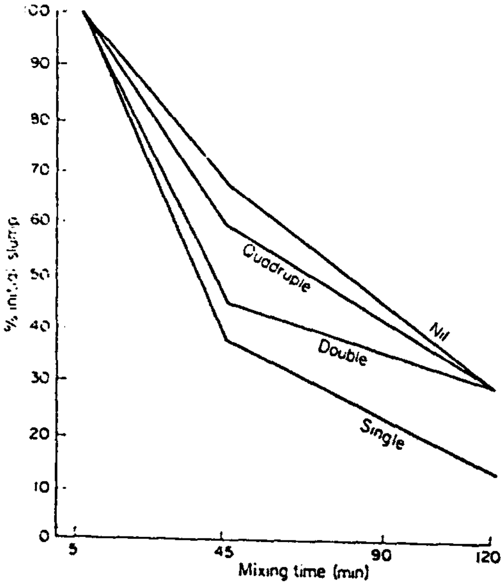


Fig. 4.7 The Effect of Different Dosage Levels on Loss of Slump [2, p 42]

Both *Figs. 4.6* and *4.7* illustrate the loss of slump from those mixes designed to initial slump equivalent to a mix containing no admixtures. However, when the water-reducing admixture has been used to increase the workability by a straight addition, although the rate of slump loss is still greater in the case of the admixture-containing mixes, the high workability is maintained for a longer time as shown in *Fig. 4.8*.

Similar results are obtained for hydroxycarboxylic acid based retarding water-reducing admixture and are shown in terms of loss of workability measured by slump test and by the VeBe in *Fig. 4.9*. The general conclusion can be reached that the use of retarding water-reducing admixture to increase the initial workability so that the

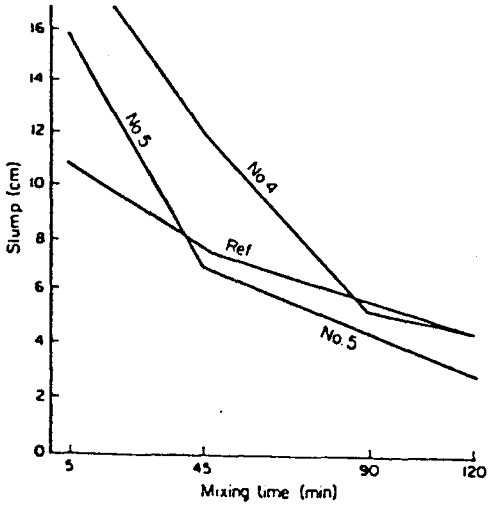


Fig. 4.8 The Loss of Slump With Time When Straight Addition of Water-Reducing Agent is Made [2, p 43]

initial rate of the slump loss is compensated for, will prolong the time available for the transporting, handling and placing of concrete. Even when these types of

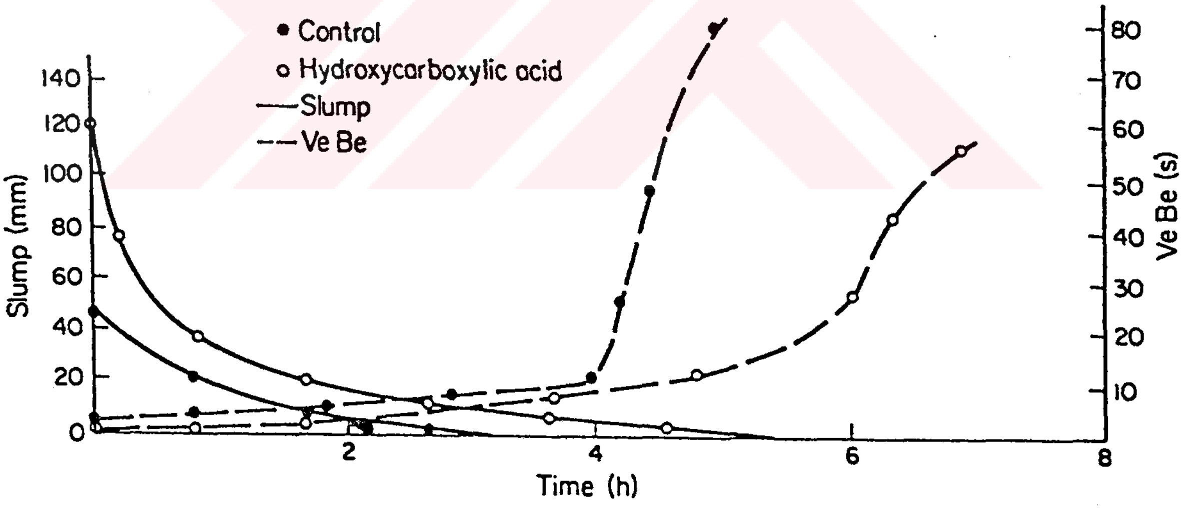


Fig. 4.9 Changes in Slump and VeBe Values for Concrete Containing Straight Addition of a Hydroxycarboxylic Acid Based Water-Reducing Agent [2,p43]

materials are used to produce concrete of normal workability, it is generally found that the increased slump loss would cause no problems in normal concrete production unless particular circumstances such as hot weather or long hauls are involved. In these cases the amount of water required to correct the loss of slump is reduced in the presence of a water-reducing admixture. This statement applies to the majority of cases, but there have been instances of severe loss of slump, which have hampered concreting operations and it has been suggested that this is more likely to occur in high alkali cements. The problem is minimized by the addition of the admixture after the mixing ingredients have been given an initial mixing cycle of 2 min.

A similar effect of loss of workability is noted in the case of superplasticized concrete of the sulphonated melamine formaldehyde or sulphonated naphthalene formaldehyde types. Often the phenomenon is more pronounced because of the extreme initial workability obtained. *Fig. 4.10* is a typical flow table against time relationship of superplasticized flowing concretes and also gives some indication of the effect of agitation.

The initial workability and subsequent workability loss of superplasticized concrete is also a function of the age of the concrete when the addition of the admixture is made. This is illustrated in ***Fig. 4.11***

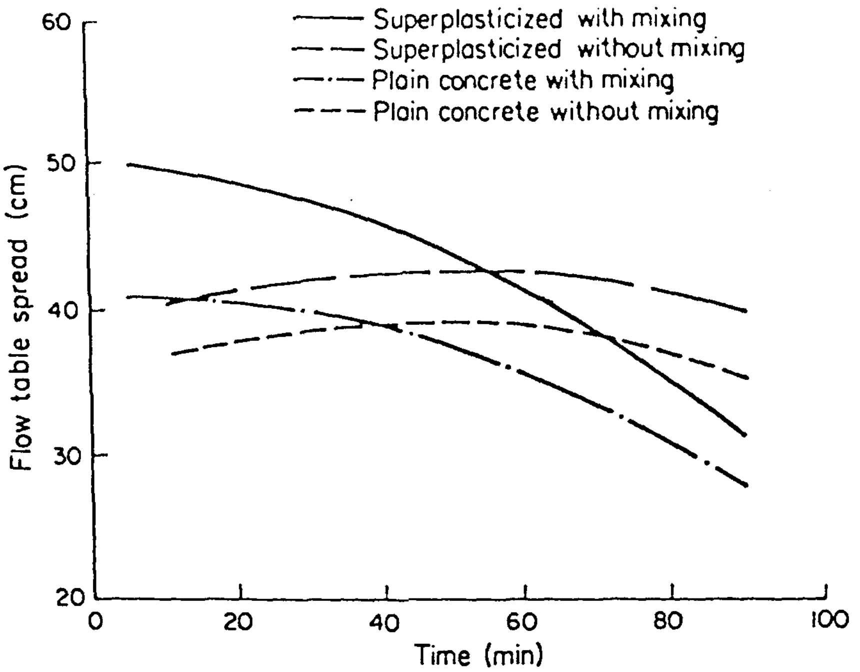


Fig. 4.10 Flow Table-Time Relationships for Plain and Superplasticized Concretes [2, p 44]

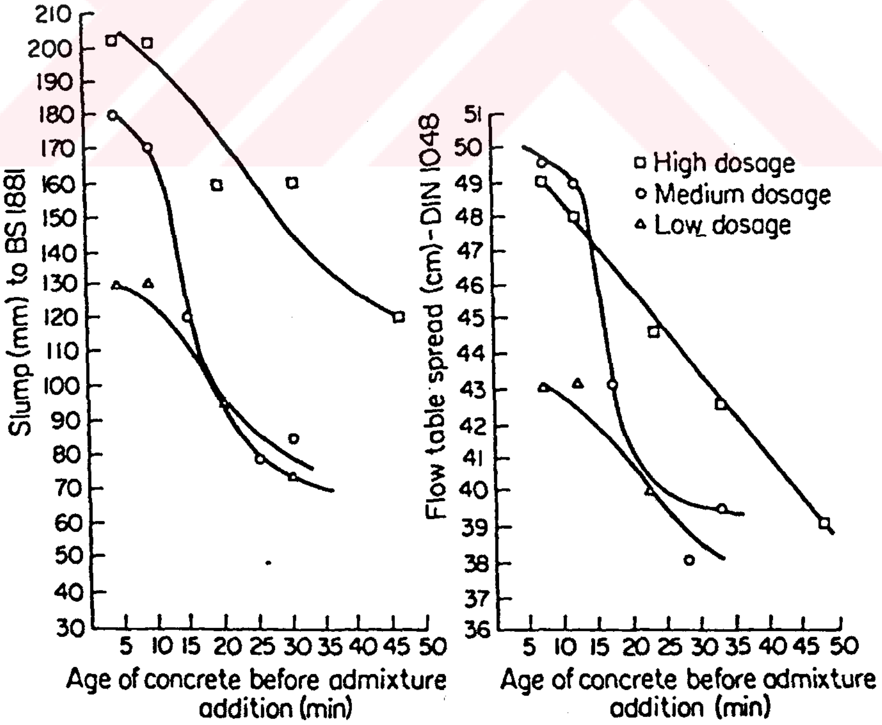


Fig. 4.11 The Effect of Age of The Concrete on the Capability To Be Rendered Flowing by the Addition of a Superplasticizer [2, p 45]

If the superplasticizer is used to produce high strength concrete of normal workability utilizing low water-cement ratios, the slump (spread) loss is again considerably increased, as shown in *Fig. 4.12.* Therefore in designing concrete of this type some allowance should be made for subsequent slump loss.

The workability loss of superplasticized concrete at various temperatures has been studied and additions of retarders made to both naphthalene and melamine formaldehyde sulphonate based superplasticizers in order to extend the period of workability. *Table 4.3* shows the effect on workability loss at various temperatures

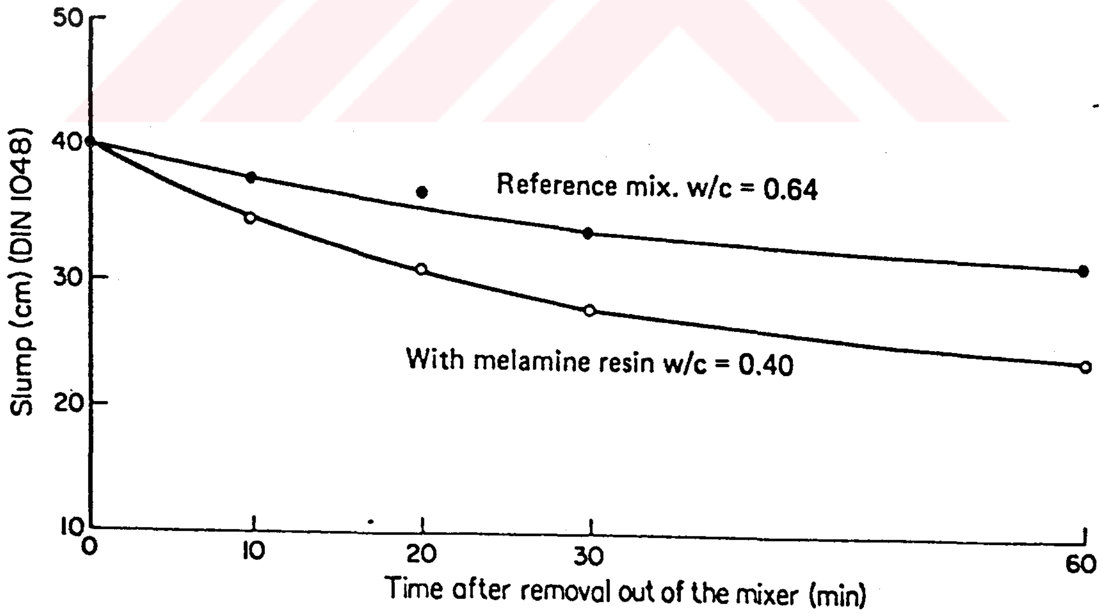


Fig. 4.12 The Workability of Superplasticized High Strength Concrete as a Function of Time [2, p 45]

Table 4.3 The Slump Loss of Superplasticized Concrete at Various Temperatures [2, p 46]

	Slump of SP concrete(mm)		
Time (h)	4°C	21°C	42°C
0	220	220	210
0.5	205	200	195
1	210	195	185
2	210	200	150
4	185	140	30

of concrete containing a specially modified naphthalene based superplasticizer whilst *Fig. 4.13* gives graphical results for the slump loss of concrete containing modified and unmodified melamine based superplasticizers.

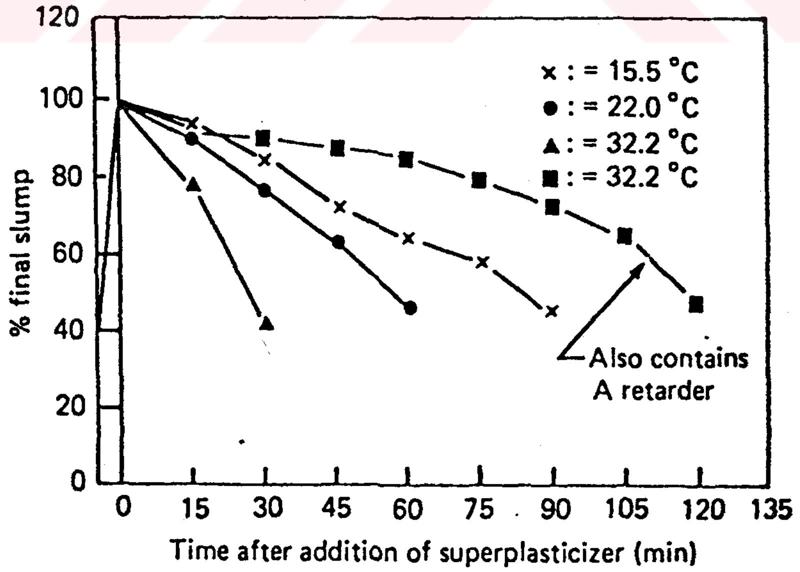


Fig. 4.13 The Slump Loss of a Melamine Formaldehyde Sulphonate Superplasticized Concrete at Various Temperatures [2, p 46]

In the practical application of flowing concrete, because of the rapid loss of the extreme workability, the admixture should be added on site just prior to placing. Alternatively, it is reported that instead of making the addition in one dose, an incremental addition which is also termed *repeated dosage*, can be made which prolongs the workability; this is illustrated in *Fig. 4.14*

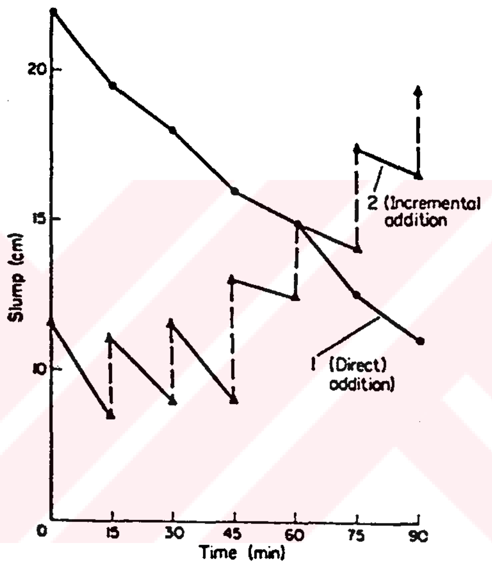


Fig. 4.14 Workability can be Maintained For a Longer Time by Incremental Addition of a Superplasticizer [2, p 47]

Water reduction

The most widely used application of water-reducing admixtures is to allow reductions in the water-cement ratio whilst maintaining the initial workability in comparison to similar concrete containing no admixture. This, in turn, allows the attainment of a required strength at lower cement content to effect economies in mix design.

The amounts of water reduction possible depend on numerous factors and these are summarized below.

(a) **The aggregate-cement ratio** : The efficiency of water-reducing admixtures, and their relative usefulness are dependent on the aggregate-cement ratio. Hydroxylated polymer and hydroxycarboxylic acid types are more effective than lignosulphonates based materials at higher cement contents (lower aggregate-cement ratios), whilst the lignosulphonate materials are generally preferred for the lower cement contents (high aggregate-cement ratio) mix designs. Typical comparative data are shown in *Fig. 4.15*.

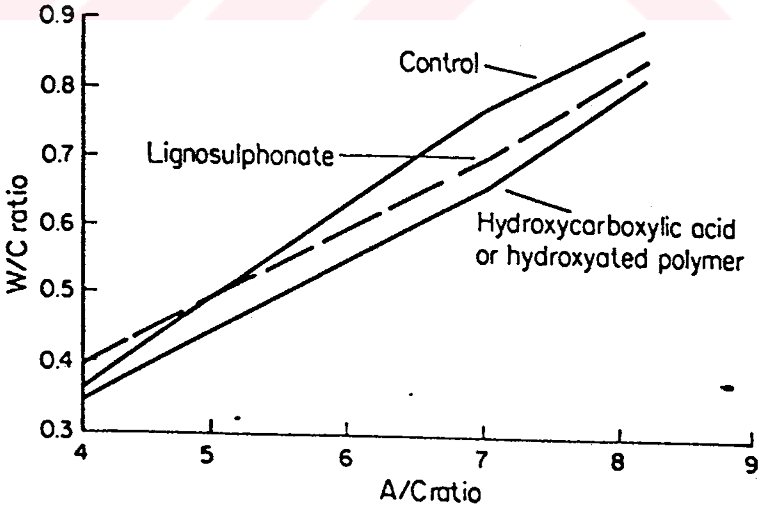


Fig. 4.15 Reduction in Water/Cement Ratio as a Function of Aggregate/Cement Ratio for Lignosulphonate and Hyroxycarboxylic Acid Based Water-Reducing Agents [2, p 48]

It can ,be seen that the water-reducing admixtures are most effective at an aggregate-cement ratio in the region of 6.5 to 7.0 in these mixes.

(b) **Design workability** : The higher the required workability, the greater is the reduction in water-cement ratio when an addition of a water-reducing admixture is made. Thus for a typical 300 kg/m^3 concrete with natural gravel aggregates and with a zone 3 sand, the typical values in *Table 4.4* would apply for a normal addition level of a lignosulphonate water-reducing agent.

Table 4.4 Water Reduction by Water-Reducing Agent [2, p 48]

Slump	% reduction in w/c ratio
50	5 - 8
75	8 - 10
100	10 - 12
150	12 - 15

c) **Additional level** : It is possible to vary the addition level of water-reducing admixtures when an increase in dosage level will generally produce an increase in the amoûnt of water which it is possible to remove from the mix proportions whilst maintaining the required slump. Typical values are shown in *Table 4.5* for an aggregate-cement ratio of 5.85:1 and a slump of 50 mm.

Table 4.5 Effect of Addition Level of Water-Reducing Admixtures on the Water Reduction [2, p 49]

Water-reducing admixture type	Addition level	W/c ratio
None		0.55
Lignosulphonate	Normal	0.51
	2 × normal	0.49
	5 × normal	0.47
None		0.55
Hydroxycarboxylic acid	2 × normal	0.48
	5 × normal	0.46

When superplasticizers are used to effect reductions in water-cement ratio, much larger decreases in the water required are obtained. The effect is dependent on the amount added as shown in *Fig. 4.15*.

Similar results for melamine formaldehyde based materials have also been reported and these data are given in graphical form in *Fig. 4.16*. It can be seen that by the use of superplasticizers considerable reductions in water/cement ratio can be obtained to produce much higher strength concrete as shown in the next section.

The amount of water reduction possible is also a function of the way in which an admixture is added to concrete; if a period between mixing with water is allowed prior to the addition of the admixture, greater adsorption of the admixture on to the initial hydrates is obtained and a higher workability or alternatively a greater reduction in water/cement ratio is obtained as can be seen from *Table 4.6*. This information is, on first

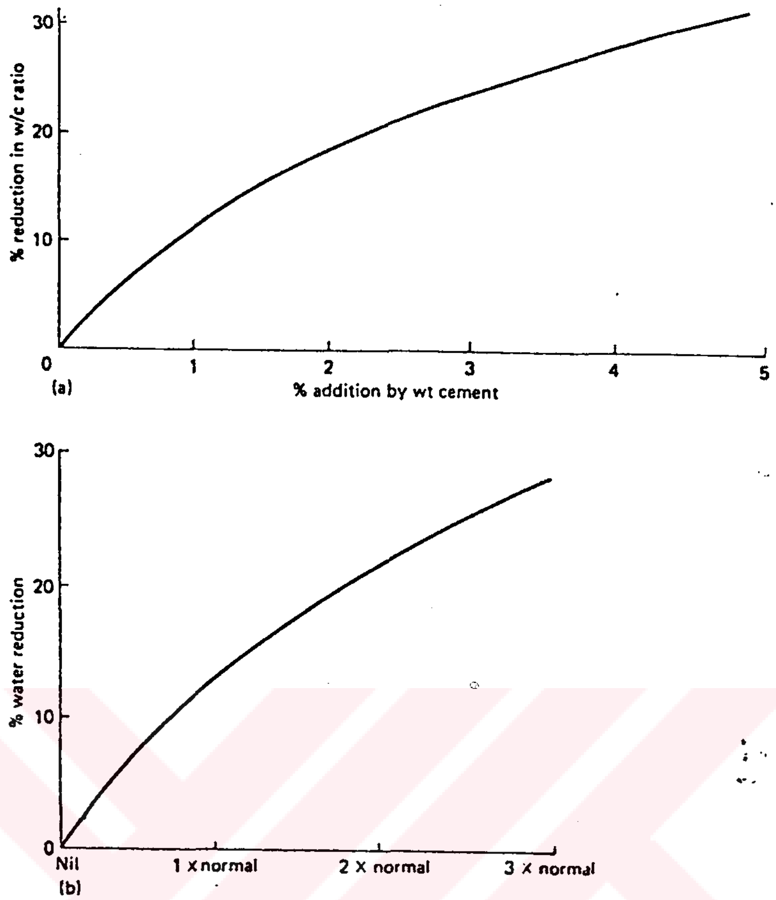


Fig. 4.16 Typical Reductions in Water/Cement Ratio Obtained by Two Types of Superplasticizers [2, p 49]

sight, in contraction to the data of superplasticizers shown in *Fig. 4.11* where the ageing of the concrete prior to superplasticizer addition appears to reduce the ability to produce flowing concrete. However, the data shown in *Fig. 4.11* start at 5 min. and it has been found with superplasticizers that if they are added to the mix water without some prior hydration period, the effect is very much reduced.

Table 4.6 Effect of Varying the Point of Addition on Workability and/or Water Reduction [2, p 50]

Method of addition of retarder (0.225% calcium lignosulphonate by wt cement)	W/c ratio	Slump (mm)	% Water reduction
No retarder added	0.59	100	—
Added with mix water	0.55	88	6.8
Addition delayed 2 min	0.55	163	6.8
Addition delayed 2 min	0.51	81	13.6

d) Cement characteristics : In the case of lignosulphonate water-reducing agents, the effectiveness in reducing the water-cement ratio diminishes with an increase in either the C_3A or alkali content. This is not an area that has been well quantified in the literature, the effect can be considerable and in a comparative experiment with three cements varying in C_3A content from 9.44 to 14.7% in comparable mixes, the percentage water reduction for a calcium lignosulphonate based material varied from 10 to 4% to achieve a similar level of workability. There is some evidence that the hydroxycarboxylic acids are less dependent on cement variables than the calcium lignosulphonate based materials. [2, p 36]

4.3. AIR ENTRAINMENT

During the mixing of concrete, the "folding" action of the mixing sequence causes air voids to be formed in the system, which in normal concrete would be reduced by the mechanical forces used in placing the concrete, leaving perhaps up to 1.5% air by the volume trapped under aggregate particles. In practice it is generally considered undesirable to allow air contents to rise much above this level for structural concrete, because of the effect on compressive strength. In North America, where air-entrained concrete is more widely used, the use of those water-reducing admixtures which have a tendency to increase air contents will necessitate the reduction of the dosage of the air-entraining agent, often by as much as 50%. On the other hand, certain superplasticizers, particularly those based on the melamine and naphthalene formaldehyde sulphonates, when used to reduce water/cement ratio, require a significant increase (up to tenfold) in dosage of the air-entraining agent to achieve normal level of entrained air.

The presence of a water-reducing admixture can alter the air content of concrete, either as a deliberate measure (the air entraining water-reducing admixtures) or as a side effect of the material in lowering the surface tension of the aqueous phase. However, a "plain" superplasticizer, even when used at dosages of about 3%, raises the air content to about 1.5% from 0.9%.

Table 4.7 Air Entrainment by Water-Reducing Admixtures [2, p 35]

Category of water-reducing admixture	Chemical type	Additional air content (% by volume)
Normal	Lignosulphonate	0.4–2.7
	Lignosulphonate + tributyl phosphate	0.3–0.6
	Hydroxycarboxylic acid	−0.2–0.3
Accelerating	Lignosulphonate + $CaCl_2$ or formate	0.3–0.5
	Hydroxycarboxylic acid + $CaCl_2$	0.8–1.6
Retarding	High sugar lignosulphonate	1–2
	Hydroxycarboxylic acid	0
	Hydroxylated polymer	−0.2–0
Air-entraining	Lignosulphonate + surfactant	0.9–2.6
	Hydroxycarboxylic acid + surfactant	3–5
Superplasticizers	Modified lignosulphonates	1–2
	Sodium naphthalene sulphonate formaldehyde condensates	1–1.5
	Sodium melamine sulphonate formaldehyde condensates	−0.1 to −0.25

The amount of air entrainment obtained will obviously vary according to the type and quantity of admixture used, as well as mix design parameters, but in general at normal dosage levels, in a 50 mm slump sand/gravel mix of 300 kg/m^3 cement content the changes in air content shown in *Table 4.7* will be observed. Where the water-reducing admixture has been added to produce a concrete of high workability, for those materials which result in an increase in the air content, approximately

1% more air will result.

The presence of entrained air will, of course, be reflected in a reduced density in the plastic and hardened concrete, which will be discussed later [2, p 34].

5. 'COST FACTORS FOR READY-MIXED CONCRETE OPTIMIZATION

5.1. COMPARATIVE COSTS OF SITE-MIXED AND READY-MIXED CONCRETE

The key factor in a decision on the merits of ready mixed versus site mixed concrete is which method is the cheaper. Clearly a cost comparison needs to be carried out. but what constitutes a valid comparison? It is at this point that differences of opinion arise in many contractor's organizations. Often ready-mixed concrete will cost X TL/m^3 whereas site mix will cost Y TL/m^3. As Y is less than X site mix must be the answer. This oversimplification of the situation often belies the truth. But comparison must be carried out as follows:

(a) Like-for-like comparison: Before any arithmetic is done, it must be established that a true *like-for-like* basis is being used. With ready-mixed concrete, the price quoted will cover, in whole or in part, the haulage items. Also, the rate of supply is variable and may be chosen to meet the highest rate with which the site can deal or, varied to meet fluctuating requirements. Ready mixed concrete has a bearing on the placing element as well. Since the site-mixed concrete can be priced solely on the basis of mixing cost and the average output anticipated from the mixer, it is necessary to arrange the basis of comparison so that both methods are on equal terms. This is only achieved, in these circumstances, by considering the whole chain of events; mix, haul, and place, taking the quantity placed in a given period of time, as the basis of comparison. At the same time, unless some tabulated format is used to provide a standard basis, it is very easy to leave out key cost factors.

(b) Intangible factors: Given as accurate as possible a *like-for-like* comparison, those items to which money cannot readily be put, yet which may arise, must now be examined. A typical checklist for ready-mixed versus site-mixed concrete could be as follows.

i) The ready-mixed prices is firm, and an estimate only so far as any additional haulage and the placing is concerned. The whole of the site mix is an estimate. how accurate will it turn out to be?

ii) The quoted ready-mixed prices is firm based on a minimum quantity only. Site-mixing assumes an average achieved output. If events cause a lesser average, great cost will arise.

iii) In the event of bad weather, or other causes preventing concrete operations, site plant and labour involved will have to be paid for whether they work or not. Only additional distribution and placing plant and labour is affected with ready-mixed concrete.

iv) How reliable will aggregate, cement, and water supplies be for site mix?

v) How reliable will the ready-mixed concrete supply be? Delays in delivery will be expensive in labour and plant standing and delay to the contract.

vi) Ready-mixed concrete must be ordered in advance. The discipline enforced should have beneficial effects elsewhere.

vii) If delays occur, ready-mixed concrete quantities can usually be increased to retrieve lost production. Site-mixed concrete plant has fixed capacity.

viii) With site mixing plant, concrete can be turned on and off at will. This is not always easy with ready-mixed concrete.

(c) **Effect on other items:** The final phase in the cost analysis is to consider what effect the use of ready-mixed concrete may have on items other than concrete and on the progress of the contract as a whole. In most cases it will be possible to evaluate these in sums of money-either savings or additional costs. Such sums then contribute to the overall cost one way or another. Factors other than those demonstrated may arise in differing circumstances and such possible implications need to be looked for when carrying out a cost comparison. In general terms, the likely items are;

i) effect on formwork-quantity and labour;

ii) effect on steel fixing

iii) is the overall contract period altered?

iv) with the quantity variation possible, can the sequence of work be varied to economic advantage? [4,p38]

5.2. METHOD OF OPTIMIZATION

Optimization is a process which aims at maximizing or minimizing an objective function. Linear programming methods are extensively used for defined optimal combinations of the variables in the objective function.

Linear programming is a mathematical technique to obtain the best solution to a problem involving limited resources. Linear programming methods are divided into two groups, namely the graphic method and the simplex method. Simplex method was used in this work since it offers a simple but efficient means of solving complex linear programming problems, by an iterative process. Therefore, it is fast and suitable for computer solutions of linear programming problems or problems which can be reduced or converted to linear programming problems.

It can be incorporated in a non-linear model to obtain a part by part linear solution. The use of linear programming can be visualized as a three stage process;

(1) *Problem Formulation* : Gathering the relevant information, learning what question need to be answered, and setting the engineering problem up as a linear program with the conditions and constraints on the

objective function.

(2) *Problem Solution* : Finding the optimal solution to this linear program.

(3) *Solution Interpretation and Implementation* : Checking that the solution to the linear program is needed as a solution to the original real problem. (and if not going back to stage (1) to refine the formulation), doing appropriate sensitivity analyses and putting the solution into practice. [11, p 8]

5.3. COST FACTORS IN READY-MIXED CONCRETE

5.3.1. Batching and Mixing

Cost of batching and mixing for 1 m^3 concrete consists of investment cost, maintenance cost and operation cost of concrete plant, transmixers and pump. Details and calculation of batching and mixing cost is given in *Appendix E*.

5.3.2. Quality Control-Control Standard and Standard Deviation

It is known that the lower the difference between the minimum strength and the mean strength of the mix the lower the cement content that need be used. The factor controlling this difference for concrete of a given level of strength is the quality control. By this is meant the control of variation in the properties of the mix ingredients and also control of accuracy of all operations which affect the strength or consistence of concrete: batching, mixing, placing, curing and testing. Significant variations in strength of concrete may arise also from inadequate mixing, insufficient compaction, irregular curing and variations in testing procedures.

Standard deviations of compressive strengths were determined as a function of characteristic strength of concrete and control standard using a formula developed based on standard deviations of strengths given in *Table 5.1* and *5.2.*

$$SD(f_{ck}, CS) = (1-2.71^{-0.06*f_{ck}}) x (3+1.3xCS) \qquad (5.1)$$

Table 5.1 Standard Deviation Values from Eq. 5.1 [27 and 28]

	CONTROL STANDARDS					
fck	Excell-ent 1	Very Good 2	Good 3	Fair 4	Poor 5	Very Poor 6
C14	2.44	3.18	3.91	4.65	5.39	6.13
C16	2.65	3.45	4.25	5.05	5.85	6.65
C20	3.00	3.91	4.81	5.72	6.63	7.54
C25	3.34	4.34	5.35	6.36	7.37	8.38
C30	3.59	4.67	5.75	6.84	7.92	9.00
C35	3.77	4.91	6.05	7.19	8.33	9.47
C40	3.91	5.09	6.27	7.45	8.63	9.81
C50	4.08	5.32	6.55	7.79	9.02	10.26
C60	4.18	5.45	6.71	7.97	9.24	10.50
C70	4.23	5.51	6.80	8.05	9.36	10.64

$$f_{cs}=0.0775+0.0225xCS$$

$$VM(f_{ck},CS)=f_{cs}\left(1-SIGN(f_{ck}-f_{ck0})\,\frac{M}{f_{cs}}\,(f_{ck}-f_{ck0})\right)$$

$$SD=\frac{(VMxf_{ck})}{(1-ZxVM)} \qquad (5.2)$$

Table 5.2 Standard Deviation Values from Eq. 5.2 [11 and 16]

CONTROL STANDARDS

fck	Excell-ent 1	Very Good 2	Good 3	Fair 4	Very Poor 5	Poor 6
C14	1.61	2.03	2.49	2.98	3.51	4.09
C16	1.83	2.32	2.85	3.41	4.02	4.67
C20	2.29	2.91	3.56	4.26	5.02	5.84
C25	2.87	3.63	4.45	5.33	6.28	7.30
C30	3.33	4.24	5.22	6.26	7.39	8.60
C35	3.77	4.82	5.95	7.16	8.46	9.86
C40	4.16	5.36	6.64	8.01	9.48	11.07
C50	4.86	6.33	7.90	9.58	11.39	13.34
C60	5.42	7.16	9.01	11.00	13.13	15.43
C70	5.85	7.85	9.98	12.26	14.70	17.34

5.3.3. Transportation, Placing and Compaction

Cost of transportation and placing is taken as the sum of cost of transportation on transmixers to an average distance of 10 km and cost of pumping 16 m vertically and 16 m horizontaly (see *section 8.9*). In Gaziantep, ready-mixed concrete producers undertake also the compaction of concrete they deliver.

5.3.4. Formwork and Scaffolding

In the cost analyses, the total cost of placed and compacted concrete should include also formwork and scaffolding costs, including the related investment and operating costs for 1 m^3.

In previous works, formwork and scaffolding unit costs were calculated by using cost analyses sheets prepared by Ministry of Public Works. The quantity of materials and worker hour values are given in these forms. The unit costs of materials and worker wages are also shown in a separate small handbook. These unit costs and required quantities for a certain type of formwork or scaffolding are multiplied and added to give the cost. A certain amount of profit is also to be added to this total cost. The number of reuses was also to be taken into account [12, p 23].

6. MIX DESIGN

6.1. MIX DESIGN METHOD

6.1.1. Maximum Aggregate

Maximum Aggregate Size from Strength Considerations:

The larger the aggregate particle the smaller the surface area to be wetted per unit weight. Thus, extending the grading of aggregate to a larger maximum size and/or fineness modulus lowers the water requirement of mix, so that, for a specified workability and richness, the water/cement ratio can be lowered with a consequent increase in strength.

Experimental results show also that, for maximum size greater than 31.5 mm the gain in strength due to the reduced water requirements is offset by the detrimental effects of lower bond area and of discontinuities introduced by the very large particles, particularly in rich mixes.

The best maximum size of aggregate from the standpoint of strength is a function of the richness of the mix. In structural concrete of usual proportions, from the point of view of strength there is no advantage in using aggregate with a maximum size greater than about 25 or 40 mm. Moreover, the use of larger aggregate would require the handling of a separate stockpile and might increase the risk of segregation [1, p 196].

Maximum Aggregate Size from the Wall Effect Considerations:

It is clear that the largest size of the aggregate particles in the concrete has to be appreciably smaller than the narrowest dimension of a form or a test specimen. Various authorities recommend different values for the ratio of maximum aggregate size to the minimum dimension of the form or test specimen.

The limitation of size arises from the "wall effect": the wall influences the packing of concrete, since the quantity of mortar required to fill the space between the particles of the coarse aggregate and the wall is greater than that necessary in the interior of the mass and therefore in excess of the mortar available in a well proportioned mix [1, p 564 and 14]. Therefore, a concrete with larger maximum aggregate size would require a larger mortar content to fill the same form or mould without extra voids.

The wall-effect can be expressed quatitatively by the ratio *D/L* where

$$L = = \frac{\textit{Volume filled by concrete}}{\textit{Total surface area of with which the concrete is in contact with pipe}}$$

which is analogous to hydraulic radius.

If $D/L > 1$ *there is strong wall-effect,*
If $0.8 \leq D/L \leq 1$ *there is wall-effect,*
$D/L < 0.8$ *the wall-effect is negligible*

6.1.2. Method of Concrete Particle Size Distribution

In the concrete type grading zones developed by Faury, passing % is taken as ordinate and the abscissa is the sieve size in the $d^{1/5}$ scale. The minimum particle size in the Faury grading curve is 0.0065 mm; it is assumed that *the minimum size of solids is 0.0065 mm including cement.*

U, V and W are points defining the Faury grading curve. The point (0.0065,0) is denoted by U. The abscissa and the ordinates of V are determined using an empirical formula. The curve is constructed drawing straight lines from U to V and V to W.

Abscissa of V is $(D/2)^{1/5}$. Ordinate of V is given by

$$P_{D/2}=A+0.17\sqrt[5]{D}+\frac{C_1}{L/D-C_2} \qquad (6.1)$$

where, D is the maximum size of aggregate, C_1 is a coefficient approximately equal to 0.015 . The term L/D in the denominator of the third term represents the wall-effect; If $D/L < 0.8$ or $L/D > 1.25$ this third term in *Eq. 6.1* may be ignored.

A' is a coefficient that depends on consistency of concrete and equipment for compaction and type of aggregate. The experimental values of A are given in *Table 6.1.* $C_2 \approx 0.70 - 0.75$.

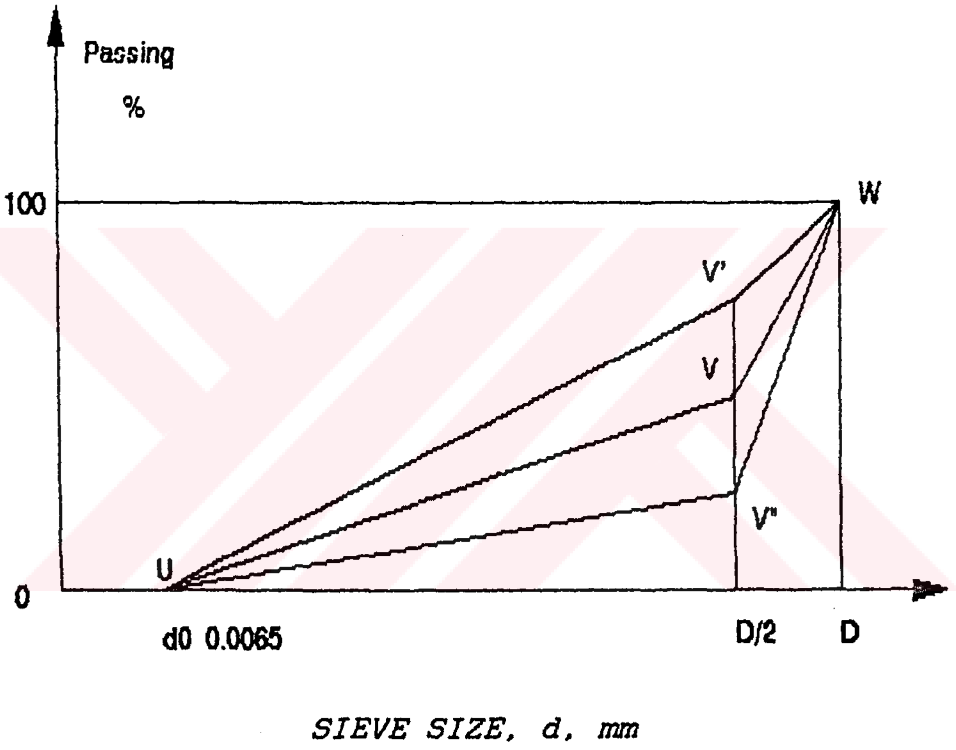


Fig. 6.1 Grading Curve for Faury Method

The ordinates for other sieve sizes between d_0 and D/2 are calculated by

$$P_d = \frac{P_{D/2}}{\sqrt[5]{D/2} - 0.365} \sqrt[5]{d} - 0.365 \tag{6.2}$$

Table 6.1 Values of A in Eq. 6.1 [14]

Consistency	Means of Compaction	For Aggregate Mix Composed of		
		Natural Sand and Coarse Aggregate	River Bed Sand and Crushed Stone Coarse Aggregate	Crushed Stone and Coarse Aggregate
Very Stiff	Vibration at High Frequency	≤ 0.18	≤ 0.19	≤ 0.20
Stiff	Strong Vibration	0.21	0.22	0.23
Plastic	Normal Vibration	0.22	0.24	0.26
Flowing	Rodding and Tamping	≥ 0.28	≥ 0.30	≥ 0.32

Then the two points V' and V" are determined by VV'= $\alpha' P_{D/2}$ and VV' = VV". For high strength concretes ($f_{ck} \leq 30$ *MPa*) concrete α'=0.15, and for normal ($f_{ck} \leq 30$ *MPa*) strength α'=0.25.

The permissible or ideal grading zone is thus defined as the area between the lines VV'W and VV"W. The concrete gradings within this zone are considered suitable under the relevant prevailing workability, wall-effect and durability conditions.

6.1.3 The Voids Content

The amount of total voids, water and air, in fresh concrete can be estimated by the empirical formula

$$V_v = \frac{K}{\sqrt[5]{D}} + \frac{K'}{\frac{L}{D} - 0.75} \qquad (6.3)$$

where V_v is the amount of total voids (W+air), m^3/m^3 conc.

K' is a coefficient (0.002-0.003)

K depends on consistency, equipment of compaction and aggregate type. $K \geq 0.24$ (see *Table 6.2*)

L is equivalent diameter of concrete section to be concreted, mm

Table 6.2 Values of K in Eq. 6.3 [14]

Consistency	Equipment of Compaction	For Aggregate Mix Composed of		
		Natural Sand and Coarse Aggregate	River Bed Sand and Crushed Stone Coarse Aggregate	Crushed Stone and Coarse Aggregate
Very Stiff	Vibration of High Frequency	≤ 0.24	≤ 0.25	≤ 0.27
Stiff	Strong Vibration	0.26	0.27	0.29
Plastic	Normal Vibration	0.27	0.29	0.29
Flowing	Rodding and Tamping	≥ 0.34	≥ 0.36	≥ 0.38

Test results obtained on concretes with 70 ~ 100 mm slump show that $V_v \approx 0.165 \sim 0.195$.

The advantage of *Faury Method* is that the wall-effect is incorporated in determination of concrete solids grading including cement and in the estimation of total voids content including air. The coefficients and limits of numerical values can be determined by statistical evaluation of test results. However, it should be noted that the higher the number of coefficients to be experimentally determined the higher the number of trial batches to be produced.

For pumpability, based on the pumpable zone specified in *Fig. 1.2* (page 24) the following relation can be used to determine the total voids, V_v, in m^3/m^3 concrete by

$$V_v = 0.6154\, V_{solids \leq 0.2mm} + (0.092 \pm 0.033) \qquad (6.3.1)$$

where $V_{solids \leq 0.2mm}$ is the absolute volume of solids in m^3/m^3 concrete, to be taken from the grading curve of the solids in the concrete.

6.2. INITIAL MIX DESIGN PROCEDURE - A WORKED EXAMPLE

The concrete mixes were designed using basically ***Faury's*** formulation with some modifications and constraints. A numerical example for the mix design procedure used in this work is given below for concrete class C14.

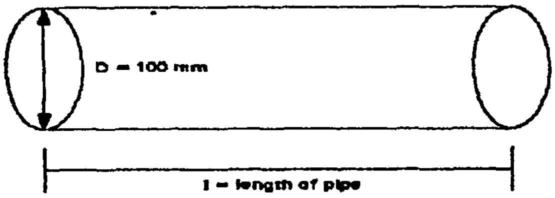
In general. type gradings are adopted for the purpose of obtaining a densest packing of solids in the mix without impairing the workability, pumpability and stability of the fresh mix. Water requirement is determined to obtain a certain required minimum workability. Minimum cement content is determined so as to satisfy the maximum durability.

Calculation of Mix Design , *For C14,* First Trial Batch

Coordinates of points on the

			$d^{1/5}$ scale
$U=(d_0,0)$	$U=(0.0065,0)$	--------->	$U=(0.365,0)$
$W=(D,100)$	$W=(31.5,100)$	--------->	$W=(1.994,100)$
$V=(D/2,P_{D/2})$			

For pumpability, the wall-effect, D/L in the 100 mm diameter pipe of the pump was allowed to be as high as 1.25 based on observations. Thus, taking a section of the pump



$$L=\frac{\pi R^2 l}{2\pi R l}=\frac{R}{2}=\frac{50}{2}=25\ mm$$

$$L=\frac{V}{S}=\frac{\text{Volume filled by concrete}}{\text{Total surface area of concrete in contact with pipe}}$$

$$\frac{D}{L}=\frac{31.5}{25}=1.26\approx 1.25$$

and the third term in the $P_{D/2}$ formula should be included

$$P_{D/2}=A+0.17\sqrt[5]{D}+\frac{B}{\frac{L}{D}-0.75}$$

where, $D=31.5$ mm (maximum particle size), $A=0.22$ (from *Table 6.1*) and $B=0.015$

$$P_{D/2}=0.22+0.17\sqrt[5]{31.5}+\frac{0.015}{\frac{25}{31.5}-0.75}=0.9026\ \frac{m^3}{m^3\ solids}$$

V=(16,0.9026) ---------> V=(1.741,0.9026)

VV'= α' $P_{D/2}$ (α'=0.25 for normal strength)

VV'=0.25x0.9026=0.22565 , $P_{V'}$=1.1283 > 1.00

V'= (D/2,$P_{V'}$) , V'=(16,1.00) ---------> V'=(1.741,1.00)

V"=(D/2,$P_{V''}$) , V"=(16,0.6769) ---------> V"=(1.741,0.678)

Estimation of voids in concrete;

$$V_v=\frac{K}{\sqrt[5]{D}}+\frac{K'}{\frac{L}{D}-0.75}$$

where, K=0.27 (from *Table 6.2*) and K'=0.0025

$$V_v=\frac{0.27}{\sqrt[5]{31.5}}+\frac{0.0025}{\frac{25}{31.5}-0.75}=0.193\ \frac{m^3}{m^3\ conc.}$$

Estimation of Water Requirement

Assuming the accidentally entrained air content, $V_{air}=0.010\ m^3/m^3$ conc.

$$V_v=\frac{(W+V_{air}\ d_w)}{d_w} \rightarrow W=(0.193-0.01)\ d_w=183\ \frac{kg}{m^3 conc.}$$

Estimation of Cement Content

Minimum cement content from durability or degree of density is

$$C=\frac{550}{\sqrt[5]{D}}=\frac{550}{\sqrt[5]{31.5}}=276\ \frac{kg}{m^3 conc.}$$

The strength condition for C14 with "fair" level of control standard $\sigma=2.98$ MPa (from Table 5.2) and using Modified Graff formula with coefficient $K_{GM}=6.861$ (from Table 7.5) and $f_{cc}=37.2$ MPa,

$$f_{ca}=f_{ck}+z\sigma$$

$$f_{ca}=(14+1.28x2.98)\ MPa$$

$$f_{ca}=17.81\ MPa$$

$$C \geq \sqrt{\frac{K_{GM}\, f_{ca}}{f_{cc}}}\; V_v\, d_w$$

$$C \geq 350\ \frac{kg}{m^3\ conc.}$$

Hence volume of cement as ratio of solids

$$c' = \frac{C}{(1-V_v)\, d_c} = \frac{350}{(1-0.193)\ 2996} \rightarrow c' = 0.1448\ \frac{m^3}{m^3 solids}$$

Estimation of Mix Proportions

Volume compatibility:

$$a'_1 + a'_2 + a'_3 + c' = 1$$

Fineness modulus:

$$a'_1 k_1 + a'_2 k_2 + a'_3 k_3 + c' k_c = k_{mix}$$

Passing at D/2:

$$a'_1 P_{D/2} + a'_2 P_{D/2} + a'_3 P_{D/2} + c' P_{D/2} = P_{D/2} mix$$

Required Mix Grading

Sieve Size, mm	31.5	16	8	4	2	1	0.5	0.25	0.125	k_{mix}
Mix Grad %	100	79	66	55	45	37	29	23	17	4.49

$$\begin{bmatrix} a_1'+a_2'+a_3'=1-0.1448 \\ 3.21a_1'+6.84a_2'+7.77a_3'=4.49 \\ a_1'+a_2'+0.2119a_3'=0.79-0.1448 \end{bmatrix} \rightarrow \begin{matrix} a_1'=0.4428 \\ a_2'=0.1459 \quad c'=0.1448 \\ a_3'=0.2665 \end{matrix}$$

Calculation of Quantities of Aggregates

$$A1=[(1-V_v)\,a_1'\;d_{a1}]=[(1-0.193)\;0.4428\;2681]=958.0\;\frac{kg}{m^3 conc.}$$

$$A2=[(1-V_v)\,a_2'\;d_{a2}]=[(1-0.193)\;0.1459\;2745]=323.2\;\frac{kg}{m^3 conc.}$$

$$A3=[(1-V_v)\,a_3'\;d_{a3}]=[(1-0.193)\;0.2665\;2722]=585.4\;\frac{kg}{m^3 conc.}$$

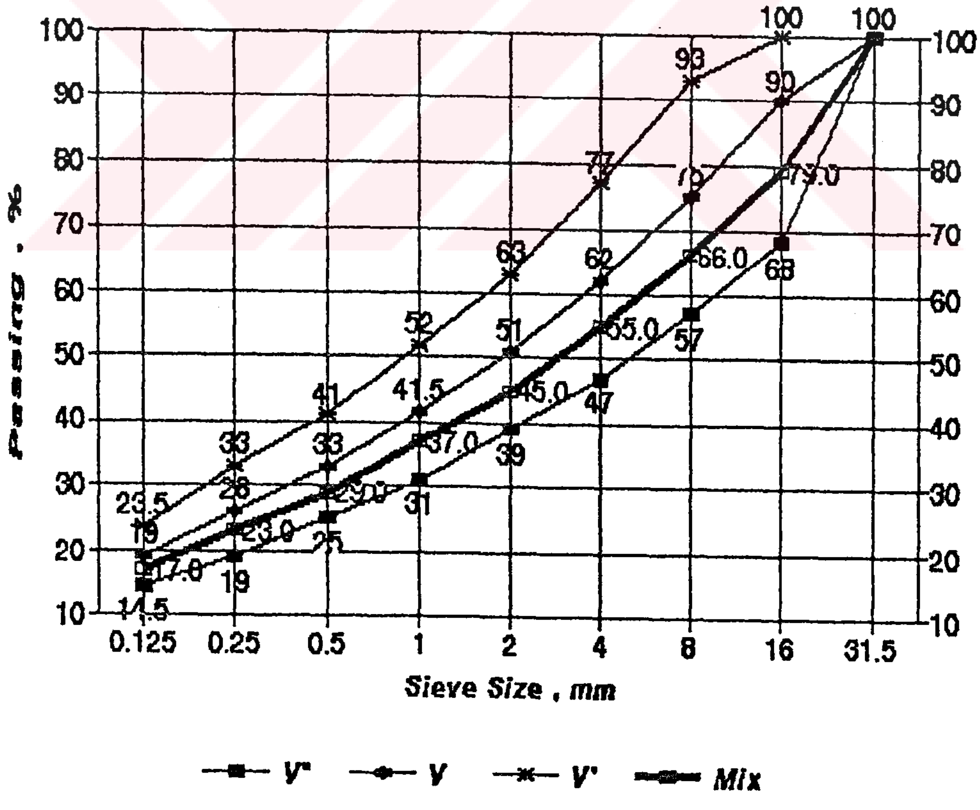


Fig. 6.2 Typical Faury Curve and Required Grading

Production of a Trial Batch Variation of Water Content to Obtain The Required Slump

These operations are repeated until the slump value required is obtained with the cement content and water/cement ratio satisfying the durability and strength requirements.

6.3. WATER REQUIREMENT

6.3.1. Bolomey's Water Requirement Formulae

The mixing water requirement W_r can be calculated on the basis of the wetting of aggregate surface by using *Bolomey's formula*:

$$W_r = \frac{NB x q}{\sqrt[3]{d_1 x d_2}} \qquad (6.4)$$

where *NB* is a coefficient between *0.075* and *0.12* as given in *Table 6.3*.

q is the weight of material with particle sizes between d_1 and d_2. In the formula d_1 and d_2 are sizes of circular mesh and used in mm. This empirical equation can be written as

$$W_{ij} = \frac{NB_i}{(d_{j-1} \ x \ d_j)^{1/3}} \qquad (6.5)$$

giving the water requirement by weight ratio for the aggrregate number i and sizes $d_{j-1}-d_j$ (or sieve number $j-1$, j), taking $d_0=0.0065$ mm.

For square mesh sieves, d_{j-1} and d_j are written as 1.25 d_{j-1} and d_j

$$W_{ij}=\frac{NB'_i}{1.16\ (d_{j-1}\ x\ d_j)^{1/3}} \tag{6.6}$$

and $NB'=NB/1.16$, NB' is given *Table 6.3*

The W_r values in *Table 6.4* have been calculated for $NB=0.1$ and $q=1$ kg. If NB is different from 0.1, the amount of water estimated should be multiplied by $NB/0.1$.

Table 6.3 Values of NB and (NB') in Eq. 6.4

Consistency	Rounded Aggregate	Angular Aggregate
Very Stiff	0.075 (0.065)	0.08–0.09 (0.07–0.08)
Stiff	0.075–0.085 (0.065–0.073)	0.09–0.10 (0.08–0.09)
Plastic	0.085–0.095 (0.073–0.082)	0.10–0.11 (0.09–0.10)
Flowing	0.095–0.105 (0.082–0.091)	0.11–0.12 (0.10–0.11)

Table 6.4 Total Water Requirement for NB=0.01 and q=1 kg in Eq. 6.6

Passing P	Aggregate Fraction (mm)	Percent Water Req. for the Size fraction (W_{ij}, wt%)	Amount of Water Req. for the Aggregate Fraction (wt% of aggregate) ($\Delta P_i x W_{ij}$)
P1	< 0.25	0.2300	P1 x 0.2300
P2 - P1	0.25 - 0.50	0.1720	(P2-P1) x 0.1720
P3 - P2	0.50 - 1.0	0.1090	(P3-P2) x 0.1090
P4 - P3	1 - 2	0.0684	(P4-P3) x 0.0684
P5 - P4	2 - 4	0.0429	(P5-P4) x 0.0429
P6 - P5	4 - 8	0.0272	(P6-P5) x 0.0272
P7 - P6	8 - 16	0.0171	(P7-P6) x 0.0171
1 - P7	16 - 32	0.0108	(1-P7) x 0.0108
		Total wt% of Aggregate	$\Sigma = 0.6774$

For spherical particles, $d_1=d_2=d$, the equation can be written as;

$$W_p=\frac{NB\ x\ q}{\sqrt[3]{d^2}} \qquad (6.7)$$

6.3.2. Water Requirement as Function of Specific Surface

The water requirement of a spherical particle is the volume of this particle with thickness t of water less its surface dry volume, i.e.,

$$W_p=\frac{\pi(d+2t)^3-\pi d^3}{6}\,\delta_W$$

where, δ_W is the density of water

Hence, the water requirement for a particle of diameter d with a film of water of thickness t on its surface,

$$W_p=\frac{\pi d^3}{6}\left(6\frac{t}{d}+12\frac{t^2}{d^2}+8\frac{t^3}{d^3}\right)\delta_W$$

If the number of aggregate particle is n_p in the fraction d

$$W_{np}=n_p \ x \ W_p$$

On the other hand

$$q=\frac{n_p \ x \ \pi \ x \ d^3}{6}\ \delta$$

where, δ is the density of the aggregate in kg/m^3

$$W_r=\left(6\frac{t}{d}+12\frac{t^2}{d^2}+8\frac{t^3}{d^3}\right)\frac{\delta_W}{\delta}$$

Knowing that $t \leq 10A^0 = 1x10^{-6}$ mm and, for normal aggregate and cement and even for silica fume $d \geq 50x10^{-6} mm$ The second and third terms in the parentheses may be neglected and

$$W=6\frac{t}{d}\ x\ \frac{\delta_W}{\delta}=\frac{t}{dx(\delta/\delta_W)}$$

is obtained. Thus, from a knowledge of t and d values of the water requirement for a fraction of mean size d can be estimated. This relation suggests that water requirement can be taken proportional to specific surface of the particles.

6.3.3. Day's Method of Determination of Water Requirement

At the core of the system is the assumption that the surface area of aggregates is the overwhelming influence on two properties of concrete, the water requirement and the cohesion (or segregation) resistance. The system is built on the following:

1) A means of establishing the surface area of each aggregate: If we consider spherical particles, halving the diameter reduces the surface area to 1/4 and volume (mass) to 1/8, i.e., it doubles specific surface which is the ratio of surface area to mass or volume as can be seen from the formulas

$$\sigma_V = \frac{6}{d} \quad , \quad \sigma_W = \frac{6}{d \cdot \gamma}$$

where σ_V is specific surface by volume and σ_W is specific surface by weight.

2) Combined Specific Surface: The combined specific surface of several aggregates is simply the sum of the individual specific surfaces multiplied by the individual weights and divided by the combined weight.

$$\sigma_{cw} = \frac{\Sigma(\sigma_{wi}\, x_i)}{\Sigma x_i}$$

or by absolute volume ratios, where σ_{wi} is the specific surface as area per unit mass and x_i is weight fraction of aggregate i.

3) Equivalent Water Factor (*EWF*): The cement content is incorporated into a factor which could be called the equivalent water factor. The formula used is

$$E=EWF=SS+0.016\ C-4$$

where SS is combined aggregate and C is cement content in kg/m^3.

This equation and subsequent equations are quite empirical and, furthermore, have not been so specifically tested as the basic specific surface factors. It is quite possible that the system could be slightly improved by modification of some of the constants. The water requirement

$$\frac{W}{F_1}=95+4.85E-0.07E^2+0.36S-0.0007S^2-8A+0.5A^2-0.1T+0.02T^2$$

where W ≡ Water content, liters per cu m

E ≡ Equivalent water factor (EWF)

S ≡ Slump in millimetres

A ≡ Air content, percent by volume

T ≡ Temperature, $^{\circ}$C

4) Strength Prediction : Basically, strength is directly proportional to Cement/Water ratio. Over the years, the strength equation has been gradually modified for the effects of varying air and cement contents. A recent version given by Day is

$$f=\frac{24F_2}{(W+0.4(A-1)C^{0.5})}\frac{-2C^2-4}{250}$$

Reasonable results for concrete in the normal strength range are given by the simple formula proposed by Bolomey

$$f=24\frac{C}{W}-8 \quad , \quad C=\frac{(f+8)\ .\ W}{24}$$

where, f ≡ 28 day cylinder strength in MPa

C ≡ Cement content, kg/m^3

W ≡ Water content, lt/m^3

A ≡ Air content, percent by volume

F_2 ≡ A factor to adjust for cement quality and effect of admixtures.

5) Mix Suitability Factor: The "other half" of the problem of mix proportioning is the suitability of the mix in the fresh state for various purposes. Everyone knows that harsh mixes segregate at higher water contents and that increased sand contents are usually necessary for pumping. The question is whether this property of cohesion or segregation resistance can be represented by a single number;

$$MSF=EWF+\frac{(A-1)}{4}$$

Table 6.5 shows mix suitability factors. The points to remember are that increasing the *MSF* costs more and has higher shrinkage but is easier to place and is more resistant to segregation.

Table 6.5 Mix Suitability Factors [20, p 28]

Mix Suitability Factor	Suitable For
16 to 17	Earth Dry Mixes under Intensive Vibration and Perhaps Pressure
20 to 22	Economical Structural Concrete
23 to 24	"American" High Slump, Easily Placed Concrete
25 to 26	Pumped Concrete
27 to 29	Flowing Superplasticized Concrete

The basic ***MSF*** may need to be increased by up to 2 for particularly badly shaped coarse aggregates or reduced by up to 2 for rounded gravel [20].

6.3.4. Water Requirement as a Function of Fineness Modulus of the Aggregate

Fineness modulus k is determined by the equation

$$k=\Sigma(1-p)$$

If the number of sieves in the set is n, then

$$k=n-\sum_{j=1}^{n} P_j \qquad (j \text{ denoting the sieves})$$

Assuming that water requirement for the aggregate is proportional to ΣP_j then, β denoting a coefficient

$$\beta\ \Sigma P_j=W_{a'}$$

$$W_{a'}=\beta\,(n-k)$$

which has the form of the relation ($W=\alpha(10-k)$) prescribed in DIN 1045 for estimating the water requirement.

6.3.5. A Generalized Approach to Water Requirement

If the amount of cement, fine and coarse aggregate is known in 1 m^3 concrete, then amount of water can be calculated by the equation

$$W=\gamma\ C+\sum_{i=1}^{n}\alpha_i\ A_i$$

For cement and the aggregate fraction passing *0.2 mm*, the water requirement coefficient is taken as *0.23*.

γ ≡ water requirement coefficient of cement, 0.23,

$$\gamma=0.23\frac{W_{rnc}}{25}\quad,\quad \gamma=0.23\frac{\sigma}{250}$$

W_{rnc} ≡ Water requirement for standard consistency of cement paste

σ ≡ Specific surface, m^2/kg

α_i ≡ Overall water requirement coefficient of aggregate *i* calculated by;

$$\alpha_i = \sum_{j=1}^{m\ sieves} (P_{ij} - P_{ij-1}) W_{ij}$$

where, P_{ij} is the passing ratio of the aggregate i through sieve j. W_{ij} is the water requirement of the $d_{j-1}-d_j$ fraction of the aggregate i, and $P_{i0}=0$ (P_{ij-1} *for* $j=1$) and $d0=0.0065$ *mm* [9, pp 194].

The coefficient α can be taken to be a function of specific surface or fineness modulus of the combined aggregate. A term $F(S)$, a function of slump, representing the water requirement for a given slump can be incorporated and $W = \gamma C + \alpha A + F(S)$ can be used as a general form [16].

7. TEST RESULTS

7.1. DETAILS OF TEST PROGRAM

In this work, Gaziantep blended portland cement (KÇ 32.5 complying with TS 10156 [22]) and locally commercially available sieved river-bed aggregate of four different size fractions (No 0, 1, 2 and 3) and tap water were used. The engineering properties of the concrete constituents are given in Table A.1. The chemical, and physical properties of blended portland cement are given in Table A.2.

The dosages used of superplasticizing admixture of modified sodium and calcium lignosulphonate type with some additions of melamine formaldehyde and naphthalene formaldehyde sulphonate condensates were 0.0, 0.25, 0.5, 1.0, 1.5, 2.0 and 5.0 % by weight of cement.

A total number of 5 concrete classes C14, C16, C20, C25 and C30 were tested. To obtain these classes, water/cement ratios of 0.58, 0.54, 0.45, 0.40 and 0.38 were used, respectively.

Basically, faury mix design procedure *Section 6.1.2.* was adopted to estimate the initial proportions.

In obtaining pumpable concretes with different SP contents, slump was chosen as 70 mm ± 10 mm. For this purpose, 10 lt trial batches were produced. Trial batches were mixed by hand at $20^{o}C \pm 2^{o}C$ temperatures and 60% ± 10% relative humidity. "True shear" [1, p 210] was taken as the indication of presence of cohesion required for pumpability. To determine the effect of temperature on slump, C14, C20 and C30 concrete batches having 0.0, 1.0, 2.0 and 5.0 % superplasticizer (SP) dosages were produced and tested at 12°C and 30°C.

For every trial batch, fresh concrete properties was tested for standard cone slump, VeBe time, unit mass and air content by the pressure method (see *section 2.2.2*).

In the experimental work, 55 lt batches of C14, C20 and C30 were produced with 0.0, 0.5, 2.0, 5.0% SP dosages and, C16 and C25 with 0.0, 2.0% SP. From each batch, one 200x200x200 mm cube, three 150x150x150 mm cubes, three 150 mm diameter cylinders (one of them for splitting tensile test, others for compression tests) and three 100x100x500 mm prisms were cast.

Specimens with 0.0, 0.5 and 2.0% SP dosages, were demoulded after 24 hours, those with 5.0% SP were demoulded after 72 hours due to the retarding effect of SP. All specimens were cured in water after demoulding at 20°C ± 2°C until the day of testing and were taken out from the water and left to become surface-dry in the laboratory atmosphere for 2-3 hours prior to testing.

Weights were measured using balances with 200 kg capacity accurate to 200 g, 30 kg capacity accurate to 20 g and 32.5 kg capacity accurate to 0.1 g.

Ultrasonic pulse transit times were measured accurate to 0.1 μs by using a digital ultrasonic concrete pulse velocity tester Model E46, with 54 kHz transducers.

Ultrasonic pulse velocities were measured in two directions, the axial and the radial (for cubic specimens the parallel and the perpendicular to the direction of casting).

An N-type Schmidt rebound hammer was used to measure the rebound number. Specimens were rigidly supported in the compression testing machine by applying 25 kN load on cylinders and 50 kN on 200 mm cubes. The surfaces to be tested for rebound number were cleared of any layer of laitance and irregularity by using a piece of abrasive stone. In all, 18 readings were made on the lateral surface of each cylindrical specimen. For the cubes, 12 readings were made on the sides (lateral surface), 6 on the top surface and 6 on the bottom. The hammer was applied in a horizontal position and perpendicular to the concrete surfaces, avoiding any large aggregate particles and visible voids, keeping 30 mm clear off the edges or ends of the specimens and the defect lines corresponding to the joints of the split mould, following the relevant RILEM and TS specifications.

The rate of loading for compressive strength was 5 kN per second on the 150 mm diameter concrete cylinder specimens and 10 kN per second on the 200 mm cube specimens, corresponding to rates of stress increase of 0.27 N/mm^2/s and 0.25 N/mm^2/s, respectively.

The rate of loading for splitting tensile strength was 2.5 kN per second on the 150 mm diameter concrete cylinder specimens, corresponding to a rate of maximum tensile stress increase of 2.0 N/mm^2/min (0.033 N/mm^2/s).

The top surface of the cylindrical concrete specimens to be tested for compressive strength were capped with cement mortar to obtain a smooth surface before the compressive test.

7.2. TEST RESULTS ON FRESH CONCRETE

7.2.1. Water Requirement Relations

The water requirement W of a concrete mix to which a superplasticizer is added was estimated by

$$W = W_0 \; (\; 1 - WR \;) \tag{7.1.1}$$

where W_0 is the water requirement, in kg/m^3 of concrete, without any addition of water-reducing agent, that is, for $WR = 0$. The relative reduction in water requirement by mass ratio, WR was expressed as a function of the superplasticizer dosage, R_{sp}, using the form

$$WR(R_{sp}) = r_\infty [1 - e^{-m_0 R_{sp}}] \tag{7.1.2}$$

It was found that WR was affected by the water/cement ratio. The values of coefficients r_∞ and m_0, were determined from experimental data for various water/cement ratios and given in *Table 7.1*.

For $W/C = 0.45$ *Equation 7.1* becomes

$$WR(R_{sp}) = 0.376\,[1 - e^{-110.4\,R_{sp}}]$$

The values of W_0 in kg/m^3 concrete were estimated by

$$W_0 = \gamma C + (\alpha_0 - \alpha_1 k_{A9}) \sum A + s_0 + s_1 S + s_2 S^2 + s_3 S^3 \qquad (7.1.3)$$

where C is the cement content in kg/m^3 concrete, k_{A9} fineness modulus of combined aggregate when a nine-sieve set with the smallest size 0.125 mm mesh is used, ΣA is the aggregate content, S is the (Abrams cone) slump in mm, and γ, α_0, α_1, s_0, s_1, s_2 and s_3 are coefficients to be determined experimentally.

Table 7.1 Typical Values of the Coefficients r_∞ and m_0 in Eq. 7.1.

NOMINAL CONCRETE CLASS	n_w=W/C	r_∞	m_0	Initial Slope $r_\infty^* m_0$
C 14	0.58	0.215	80.9	17.4
C 16	0.54	0.279	60.6	16.9
C 20	0.45	0.376	110.4	41.5
C 25	0.40	0.284	80.4	22.8
C 30	0.38	0.278	105.0	29.2

Examples for $C \geq 275$ kg/m^3 concretes, with $50mm \leq S \leq 175mm$ and $k_{A9} \approx 5.2 \pm 0.2$ are

$$W_0=0.1119C+(0.11874-0.0204k_{A9})\sum A+ \\ +82.59+1.015\,S-0.00608\,S^2+1.37\times10^{-5}\,S^3 \qquad (7.2)$$

and, assuming that the W intercept should be zero when all variables are zero,

$$W_0=0.1454C+(0.1676-0.0245k_{A9})\sum A+ \\ +1.536\,S-0.01\,S^2+2.25\;10^{-5}\,S^3 \qquad (7.3)$$

for the concretes produced in this work.

The coefficient γ representing the water requirement due to cement can be expressed as a function of water requirement for standard consistency, w_{sc}, or specific surface, σ, as

$$\gamma=\gamma_{0c}w_{sc} \quad , \quad \gamma=\gamma_{0s}\sigma$$

by which small variations in water requirement due to variations in the fineness and/or reactivity of cement can be taken into account [17].

If the general form of Eq. 7.2 is rearranged as 7.3.1,

$$W_0=\frac{n_W[\alpha(1-V_{air})d_A+F(S)]}{n_w-\gamma+\alpha\,d_A\left(\frac{1}{d_C}+\frac{n_w}{d_W}\right)} \qquad (7.3.1)$$

general trend of slump versus water requirement W_0 relation (*Eq. 7.3.1*) is shown in *Fig. 7.1* where W/C=n_w=0.58, V_{air}=0.01 m^3/m^3 conc., d_W=1000, d_C=2996, d_A=2715 kg/m^3.

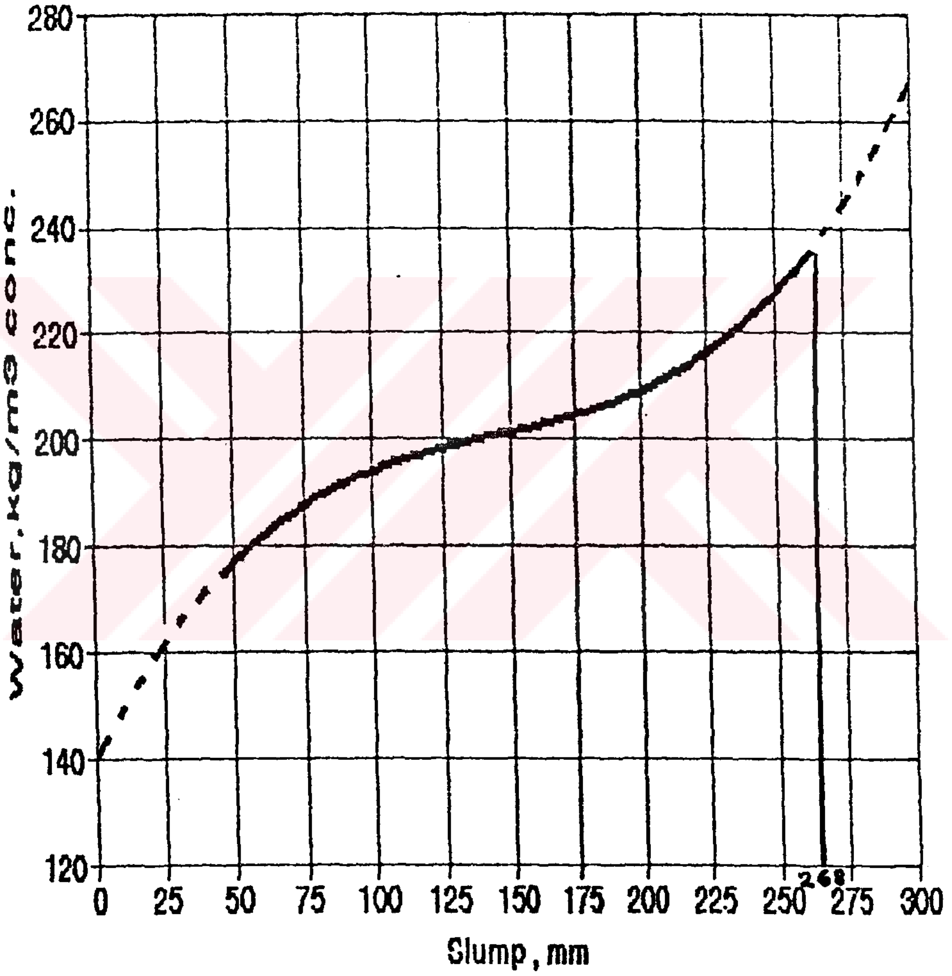


Fig. 7.1 Slump versus Water Requirement Relation

This form of 3rd degree polynomial representation for the effect of slump is based on the experimentally observed fact as described below:

For some small water content values the slump is zero. Beyond a certain water content, slump starts increasing above zero at a decreasing rate and this increase in slump continues up to a slump of 125-175 mm. At still higher water contents, depending also on the fines and admixture contents, the increase in slump slows down for the same increment in water content. Theoretically, the slump may increase up to 300mm $-D_{max}$ as water content increases.

The relative water reduction functions have been plotted in *Fig 7.2* showing the general trends corresponding to various water/cement ratios.

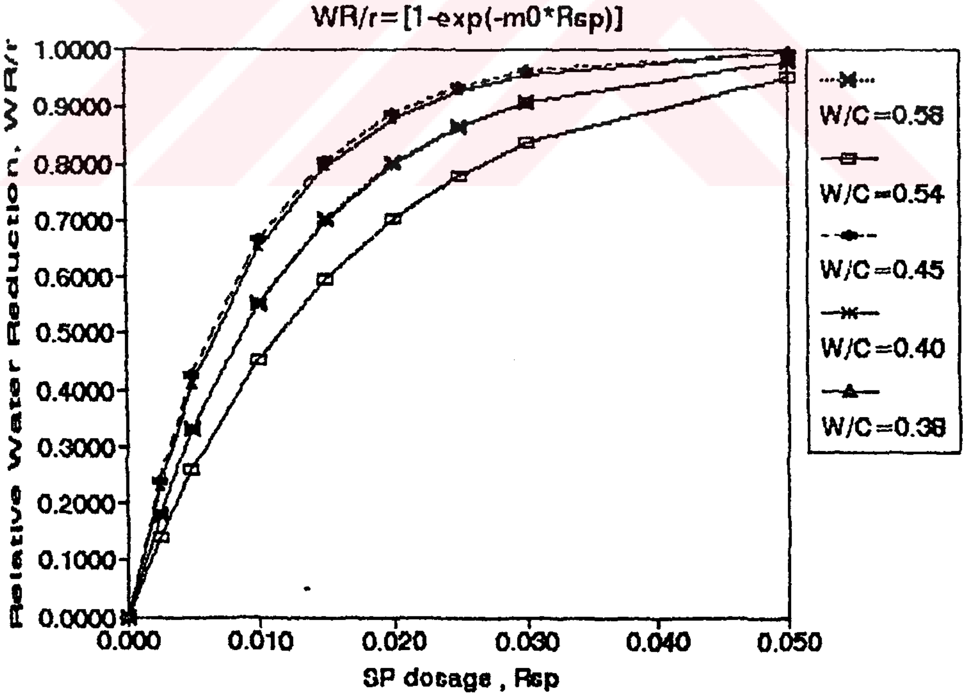


Fig. 7.2 Superplasticizer Dosage versus Relative Water Reduction

The reduction in water requirement induced by the modified superplasticizer is more pronounced in rich mixes, though total reduction shows a maximum for the moderately rich mix of concrete with water/cement ratio of 0.45.

The initial slope, $r_{\infty} {}^{*} m_0$, of the water reduction representing the efficiency of admixture at low dosage is, in general, higher in richer mixes but decreases as the W/C decreases beyond 0.45, probably due to increased rate of initial hydration and solids surface area. The rate of loss of efficiency with increasing W/C ratio may be due to the increased tendency of segregation in the cement paste.

7.2.2. Slump - VeBe Time Relation

As mentioned in *Section 2.2.2.* , VeBe time decreases with increasing slump. Therefore the slump-VeBe time relation was estimated by a power function of the form

$$VeBe=\alpha\ S^{-\beta} \qquad (7.4.1)$$

where S is the slump in mm and $VeBe$ is the VeBe time in seconds, α, β are coefficients to be determined by experimentally. A relation was constructed as

$$VeBe=70.9876\ S^{-0.72023} \qquad (7.4.2)$$

from experimental data.

A plot of *Eq. 7.4* and the experimental points are shown in *Fig. 7.3* and a statistical assessment of the relation can be seen in Tables B.2 and B.3.

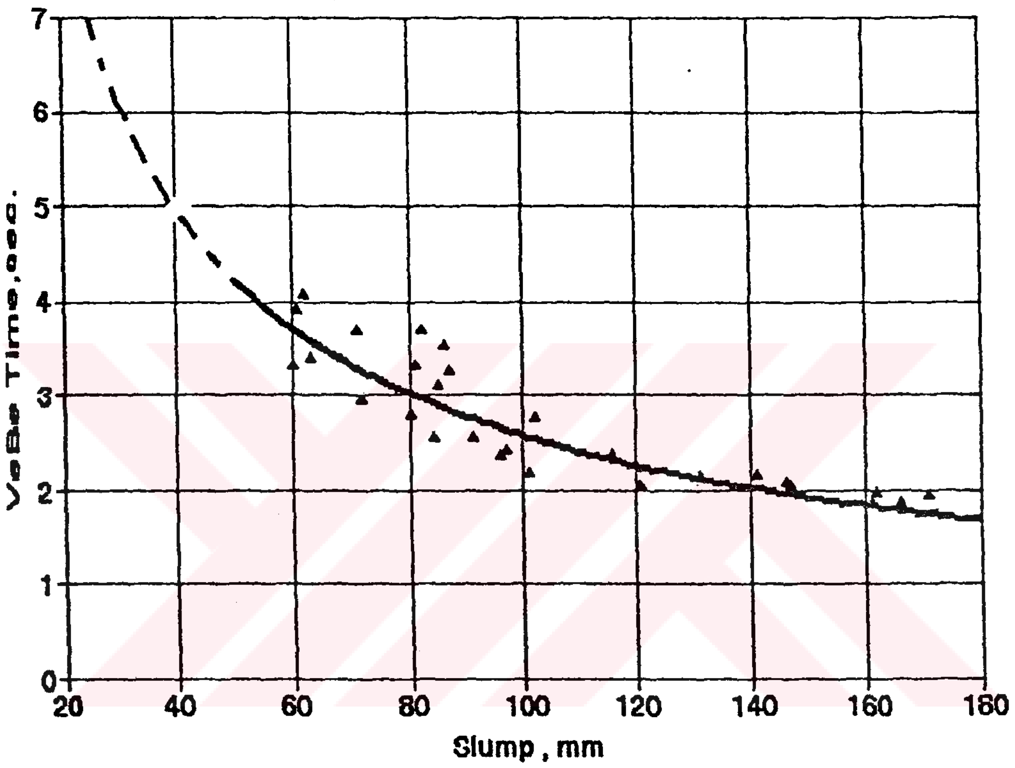


Fig. 7.3 Slump versus Vebe time Relation

As shown in *Fig. 7.3*, VeBe time decreases with increasing slump at a decreasing rate up to 100 mm beyond which the relation assumes a linear shape. However, we have to note again (see Section 2.2.2) that, VeBe test is not suitable for higher workability for conretes, especially for those with slumps exceeding 140 mm.

7.2.3. Effect of Temperature on Slump

The materials and the equipment were kept in a temperature controlled room for not less than 12 hours prior to testing. Batches of the same composition as the control concretes were produced at 12°C and 30°C and slumps were measured at the end of 10–15 minutes after mixing. The test results are shown in *Table 7.2*

Table 7.2 Effect of Temperature on Slump

		SLUMP , mm											
		C14				C20				C30			
°C		0%	1%	2%	5%	0%	1%	2%	5%	0%	1%	2%	5%
12		65	20	25	65	90	40	20	0	30	30	25	25
20	*control*	75	70	70	80	75	75	75	60	70	75	70	65
30		25	5	2	7	15	2	0	2	8	1	0	1

In general, a change in temperature results in a reduction in slump. The reduction in slump is more significant for 30°C and at higher SP dosages.

7.2.4. Relation for Estimating Entrained Air Content

The air content, V_{air} needs to be estimated in concrete mix design. An empirical formula was investigated for estimating V_{air} as a function of R_{sp} and n_w. The mathematical form

$$V_{air}=\alpha_1 n_w+\alpha_2 n_w^2+\beta_1 R_{sp}+\beta_2 R_{sp}^2$$

was taken first. where $C \geq 275\ kg/m^3$ concrete. for $50\ mm \leq S \leq 175\ mm$ and $kA9 \approx 5.2 \pm 0.2$,

$$V_{air}(\%)=(6.0358n_w-8.9982n_w^2+ \\ +230.848R_{sp}-1687.06R_{sp}^2) \qquad (7.5)$$

where n_w=W/C ratio.

Also V_{air} is plotted as a function of n_w and R_{sp} in Fig. 7.4

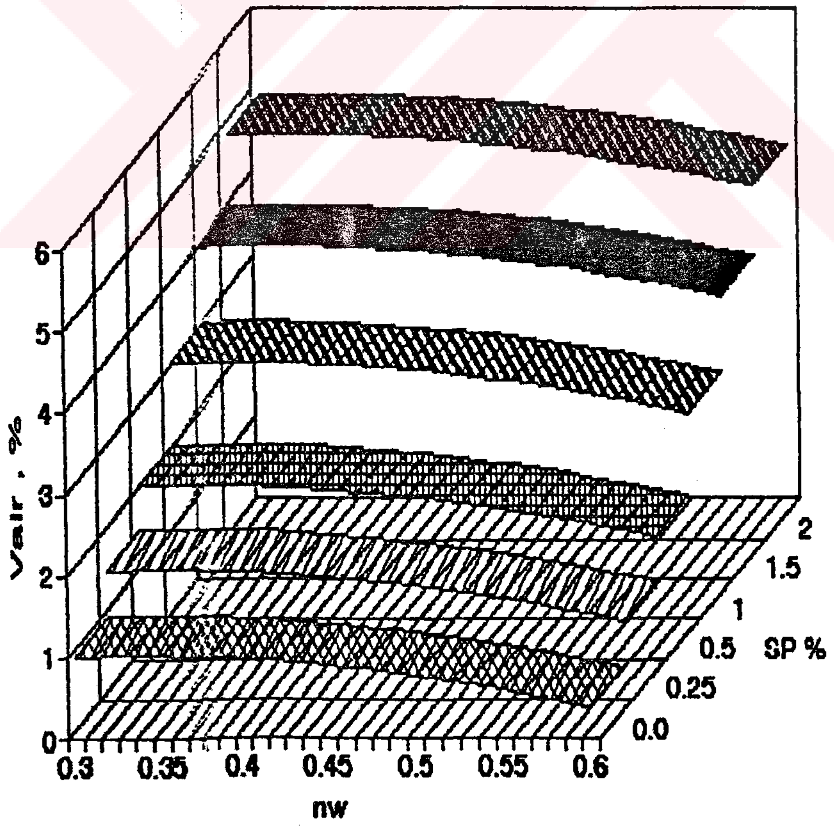


Fig. 7.4 Entrained Air Content as Function of Water/Cement Ratio and Superplasticizer Dosage from Eq. 7.5

Table 7.3 Experimental and Estimated Values of V_{air} by volume % using Eq. 7.5

	R_{sp}							
n_w	0.0		0.005		0.02		0.05	
	EXP	EST	EXP	EST	EXP	EST	EXP	EST
0.58	0.51	0.47	1.99	1.59	7.34	4.42	7.35	7.80
0.54	0.97	0.64		1.75	8.67	4.58		7.96
0.45	1.13	0.89	1.48	2.01	7.98	4.84	8.54	8.22
0.40	0.98	0.97		2.09	5.88	4.92		8.30
0.38	1.03	0.99	2.14	2.11	7.73	4.94	13.62	8.32

Entrained air content increases from about 1% in no-admixture mixes to 5% at 2% superplasticizer dosage. It is also apparent that there is an increase of 0.5% in entrained air content for a decrease of W/C ratio from 0.58 to 0.38. This increase is not significant when compared with that due to superplasticizer.

Entrained air content exceeds 3% for superplasticizer dosages above 0.8-1.0% for W/C=0.38-0.58 (see *Appendix C*).

It appears that the superplasticizer used in this work can be an "air-entraining superplasticizing" agent.

7.2.5. Relation Between A(gr) and A(pr)

To establish the relation between the air contents determined by the gravimetric method, A_{gr}, and that by the pressure method, A_{pr}, on 10 and 55 lt concrete batches,a relation of the form

$$Y(x)=\alpha_0+\alpha_1 x+\alpha_2 x^2 \qquad (7.6)$$

was adopted. The coefficients α_0, α_1 and α_2 are shown in *Table 7.4*

where A_{pr} ≡ air content determined by the pressure method using *B* type air content meter.

A_{gr} ≡ air content determined by the gravimetric method by calculation.

Table 7.4 Coefficients α_0, α_1 and α_2 in Eq. 7.6

	α_0	α_1	α_2	Eq. no
$A_{gr}(A_{pr})$	0.0394	0.4634	0.08340	(7.6.1)
				10 lt
$A_{pr}(A_{gr})$	1.1878	0.7701	-0.00505	(7.6.2)
$A_{gr}(A_{pr})$	-0.7241	1.0282	0.01260	(7.6.3)
				55 lt
$A_{pr}(A_{gr})$	0.8849	0.7734	0.01051	(7.6.4)

The A_{gr} and A_{pr} values obtained on batches of 10 lt and 55 lt are plotted in *Fig. 7.5* and *7.6*.

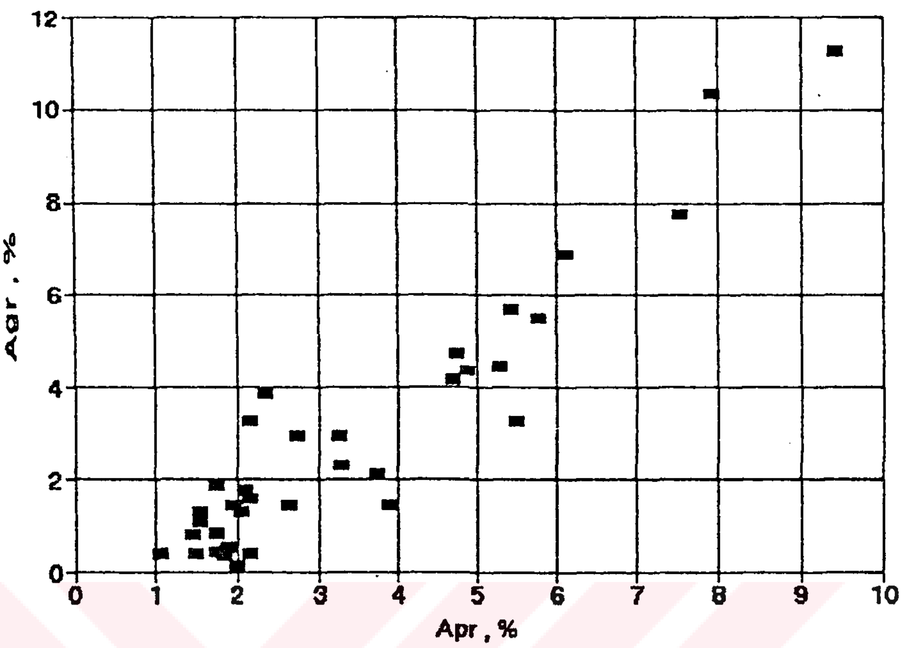


Fig. 7.5 10 lt A_{gr} versus A_{pr}

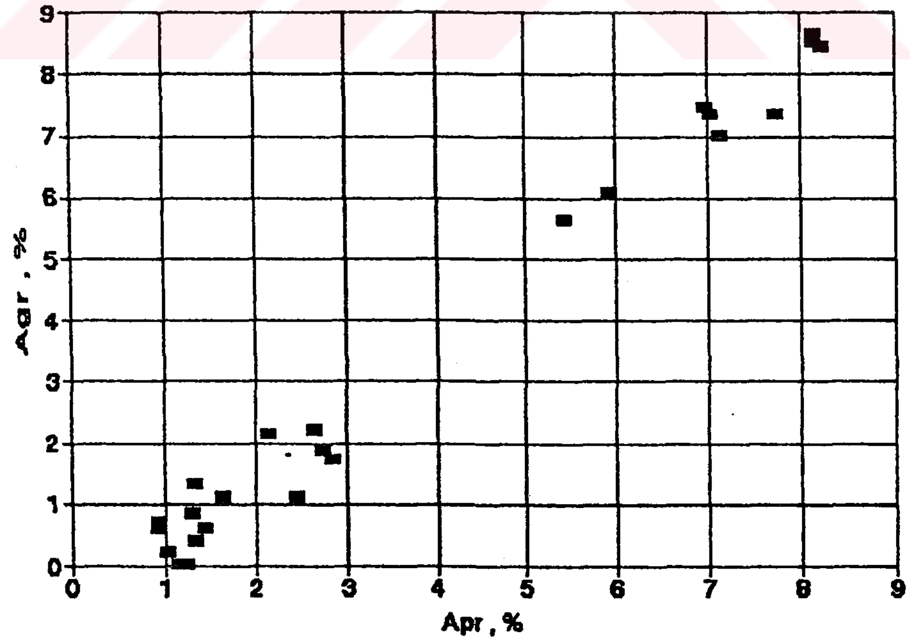


Fig. 7.6 55 lt A_{gr} versus A_{pr}

7.3. EVALUATION OF TEST RESULTS ON HARDENED CONCRETE

7.3.1. Compressive Strength

Compressive Strength C/W Ratio Relations:

For the estimation of compressive strength *f* of a concrete mix the coefficients of following strength formulae were investigated using the test results:

Graff Formula:

$$f=\frac{f_{cc}}{K_G}\left(\frac{C}{W}\right)^2 \tag{7.7}$$

Modified Graff Formula:

$$f=\frac{f_{cc}}{K_{GM}}\left(\frac{C}{W+d_W\cdot V_{air}}\right)^2 \tag{7.8}$$

Feret Formula:

$$f=K_F\left(\frac{C}{C+W+V_{air}}\right)^2 \tag{7.9}$$

Bolomey Formula:

$$f=K_{B1}\left(\frac{C}{W+d_W\cdot V_{air}}+K_{B2}\right) \tag{7.10}$$

where f_{cc} ≡ compressive strength of cement used, 37.2 MPa

K_G, K_{GM} ≡ coefficients of the Graff formulae to be determined experimentally,

K_F ≡ coefficients of the Feret formulae to be determined experimentally, MPa

K_B ≡ coefficient of the Bolomey formulae to be determined experimentally

C ≡ cement content in kg/m^3 conc.

W ≡ water content in kg/m^3 conc.

d_w ≡ density of water, kg/m^3

V_{air} ≡ volume of air, m^3/m^3 conc.

c, w ≡ volume of cement and water in m^3/m^3 conc.

Bolomey Formula's coefficients calculated from experimental data

$$f=15.9309\left(\frac{C}{W+d_w.V_{air}}-0.493\right) \qquad (7.11)$$

It was observed that K_G, K_{GM} and K_F were influenced by the superplasticizer dosage R_{sp} as can be seen in *Table 7.5*. A relation of the form

$$K=\alpha_0+\alpha_1 R_{sp}+\alpha_2 R_{sp}^2$$

was adopted to estimate the values of K as functions of R_{sp} in this study in which $C \geq 275$ *kg/m*^{3} *conc.* , 50 *mm* $\leq S \leq 175$ *mm* and $k_{A9} \approx 5.2 \pm 0.2$. Hence

$$K_G=7.2816-204.052R_{sp}+17464.28R_{sp}^2 \qquad (7.12)$$

$$K_{GM}=6.860907-350.174R_{sp}+10853.35R_{sp}^2 \qquad (7.13)$$

and

$$K_F=145.451+3687.097R_{sp}-107223R_{sp}^2 \qquad (7.14)$$

Table 7.5 Values of the Coefficient in the Empirical Cylinder Strength Formulae

R_{sp}	K_G	K_{GM}	K_F
0.0	7.282	6.861	145.45
0.005	6.698	5.381	161.21
0.02	10.186	4.199	176.30
0.05	40.740	16.486	61.75

It is apparent from the K_{GM} and K_F values in *Table 7.5* that the use of superplasticizer (Betek flu - 108) resulted in an increase of 60% in $1/K_{GM}$ and 20% in K_F for an increase in SP dosage from 0.0% to 2.0% when the effect of entrained air is taken into account. However, there is an increase of only 8% in the value of $1/K_G$ up to 0.5% SP dosage.

For higher superplasticizer dosages, especially for R_{sp}=0.05 the retarding effect cancels the improvement in strength due to better dispersion of fines including cement in concrete.

Relation between Cylinder and Cube Strengths:

The 28-day cylinder (150 mm diameter) compressive strengths were taken as the basis and relations between 200 mm cube

$$f_{cyl}=0.8518f_{cube200} \qquad (7.15)$$

$$f_{cyl}=0.6049f_{cube200}^{1.1079} \qquad (7.16)$$

$$f_{cyl}=0.3015+0.8406f_{cube200} \qquad (7.17)$$

and between 150 mm cube

$$f_{cyl}=0.7718f_{cube150} \qquad (7.18)$$

$$f_{cyl}=0.3150f_{cube150}^{1.2763} \qquad (7.19)$$

$$(7.20) \qquad f_{cyl}=0.6411+0.7502f_{cube150}$$

were obtained between the cube and cylinder strengths using the test results obtained on 15 batches or groups of concrete each having 4 cylinder, 6 150-mm cube and 2 200-mm cube specimens. All results are shown in *Fig 7.7, Fig 7.8 and Fig 7.9*.

The relation between $f_{cube200}$ and $f_{cube150}$ was investigated based on the same form yielding,

$$f_{cube200}=0.900f_{cube150} \qquad (7.21)$$

The mean cylinder strengths at 28 days and coefficient of variation of cylinder strengths are given in *Table 7.6*.

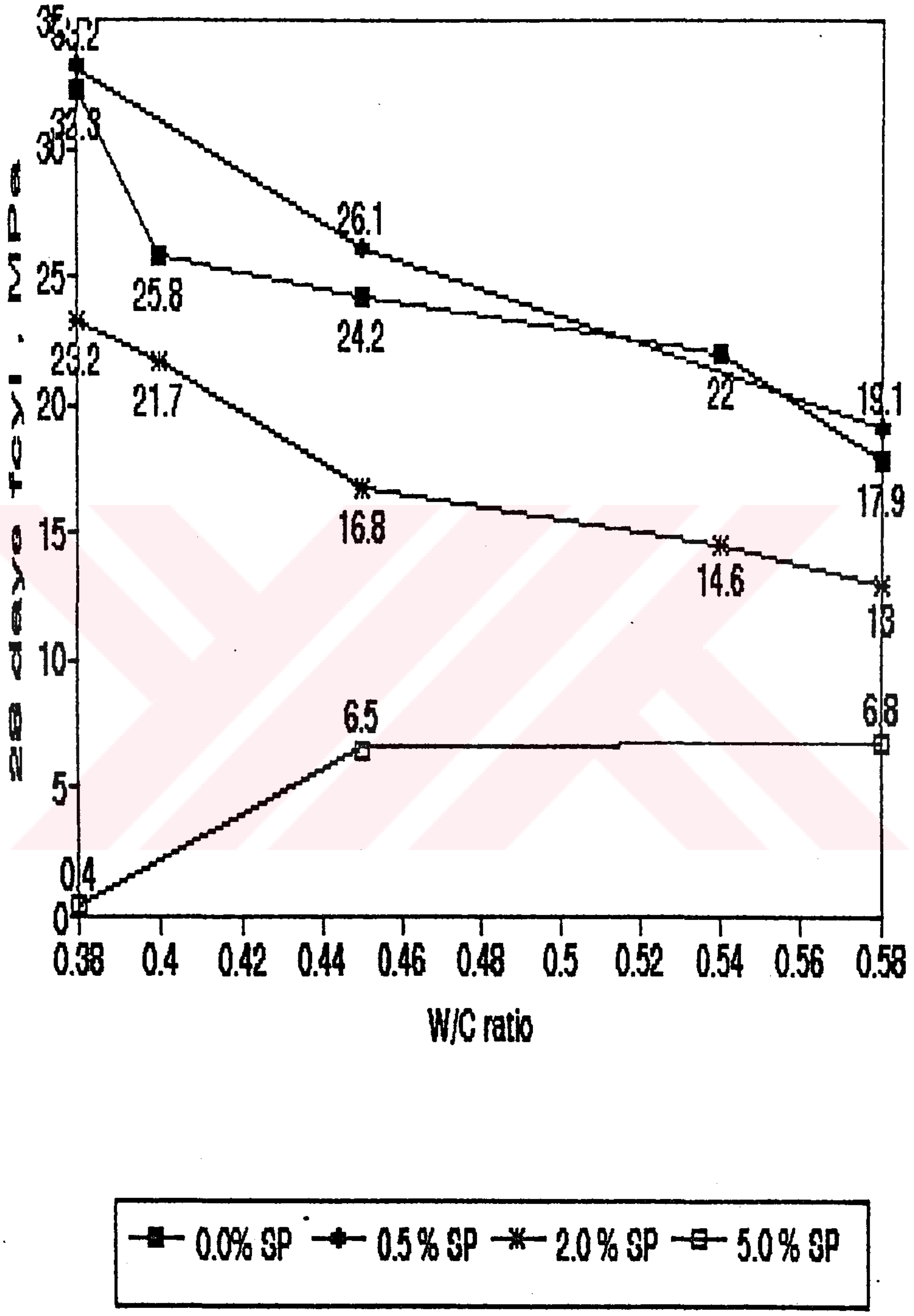


Fig. 7.7 Cylinder Strength versus Water/Cement Ratio as Function of Superplasticizer Dosage

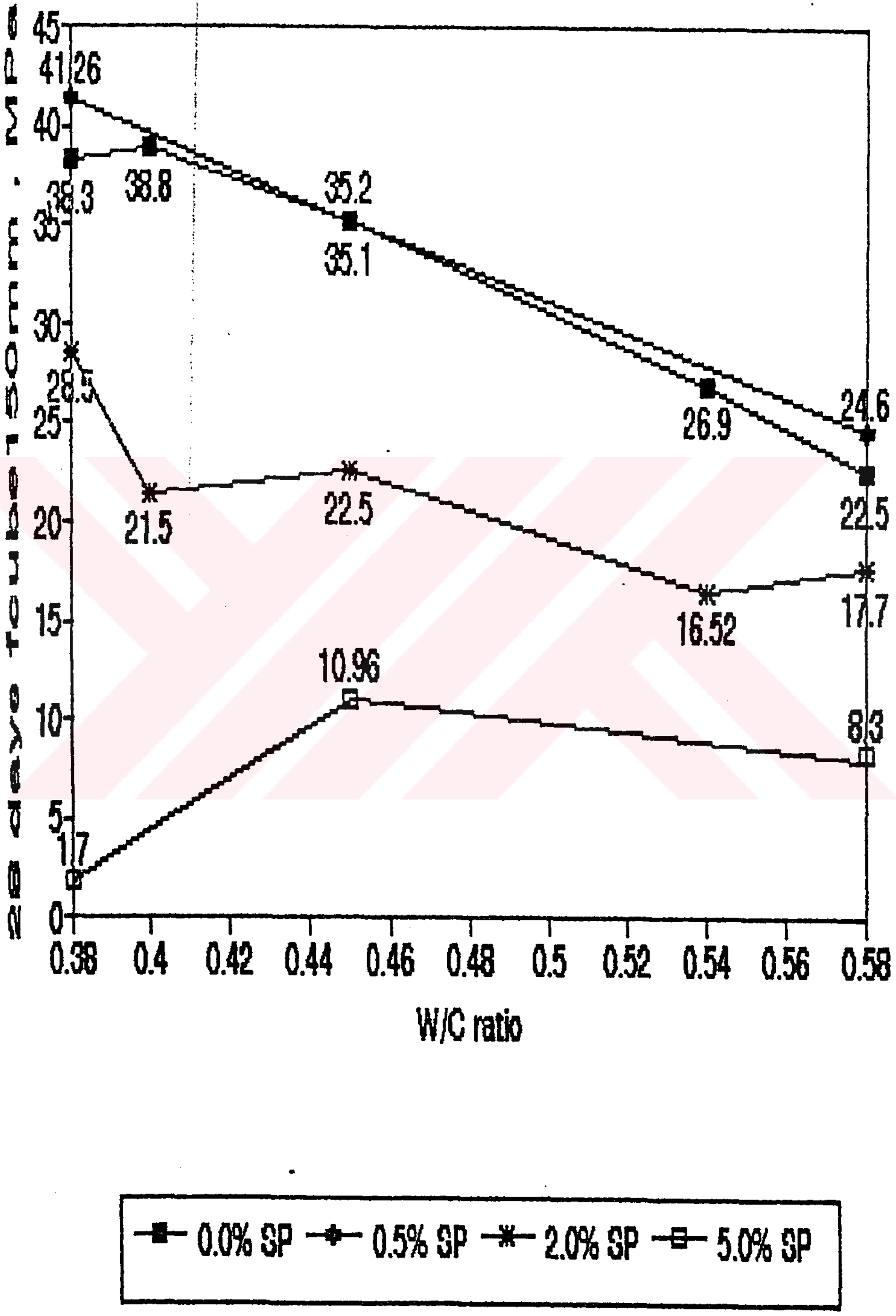


Fig. 7.8 150-mm Cube Strength versus Water/Cement Ratio as Function of Superplasticizer Dosage

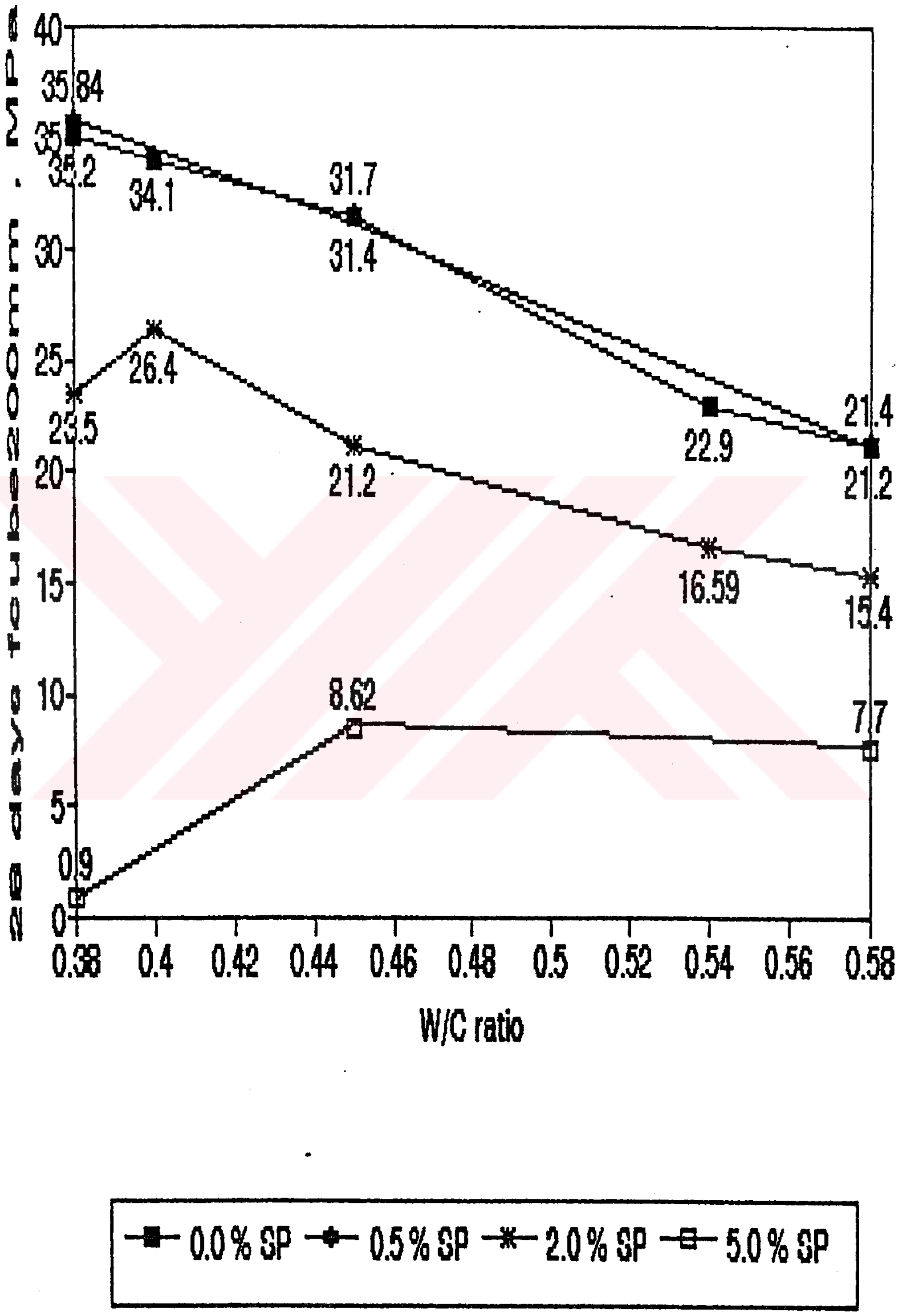


Fig. 7.9 200-mm Cube Strength versus Water/Cement Ratio as Function of Superplasticizer Dosage

Table 7.6 Coefficients of Variation of Cylinder Strengths

	R_{sp}					
W/C	0.0		0.005		0.02	
	fcm	σ/fcm	fcm	σ/fcm	fcm	σ/fcm
0.58	17.87	8.416	19.11	5.735	13.04	11.380
0.54	22.01	2.940			14.61	0.862
0.45	24.19	5.188	26.08	4.655	16.75	7.743
0.40	25.76	1.359			21.65	2.661
0.38	32.34	2.690	33.18	3.424	23.21	7.807

Based on the laboratory test results given in *Table 7.6* a general decrease is observed in coefficients of variations as the strength increases (or water/cement ratio decreases). Assuming that the control standard is "excellent" under laboratory conditions where the mix proportions are under strict control, there seems to be an intrinsic tendency of heterogeneity in lower concrete classes, especially in C14. The trends under site conditions would of course be different, but lean mixes of low strength concretes should be expected to have higher coefficient of variation.

7.3.2. Evaluation of Splitting Tensile Test Results

A general discussion of splitting tensile strength was given in *Section 3.3.2.* The test results are given in *Table 7.7.* A plot of the results are shown in *Fig. 7.10*

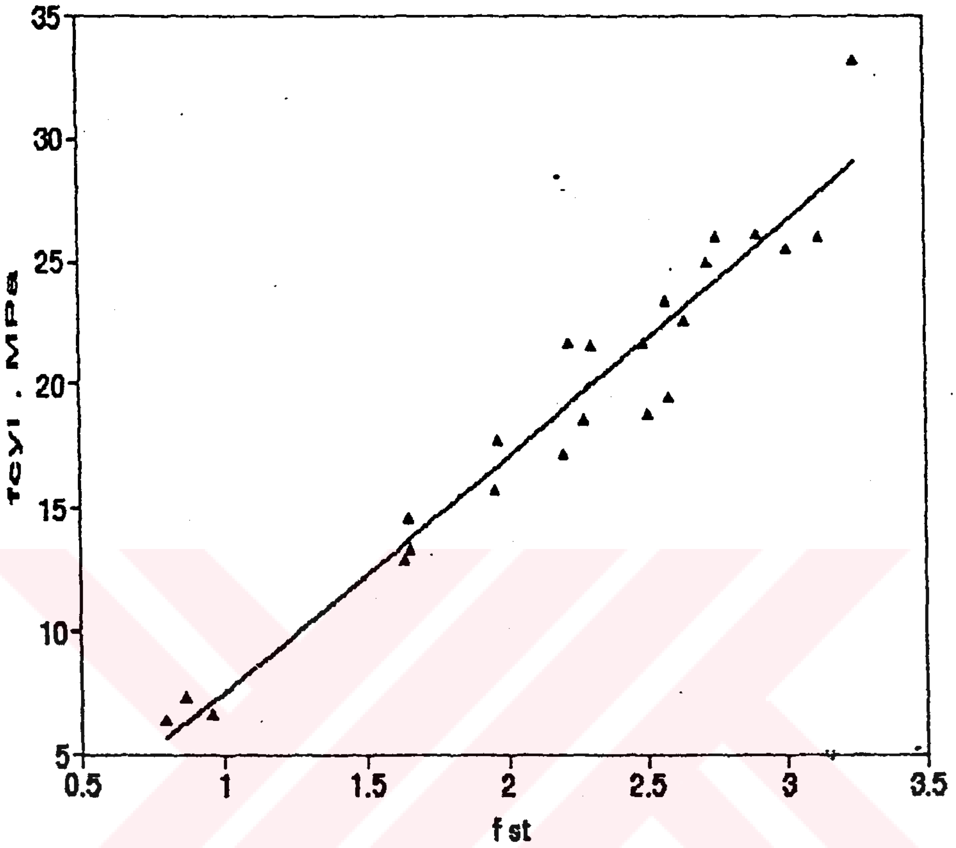


Fig. 7.10 Cylinder Compressive Strength versus Splitting Tensile Strength.

A linear fit for the data from 29 batches is

$$f_{cyl}=0.8396+8.9085f_{st} \qquad (7.22.1)$$

$$f_{st}=0.3756+0.0876f_{cyl} \qquad (7.22.2)$$

with a coefficient of correlation of 0.7803 (see *Appendix B.2*).

Compressive strength is easier to determine, therefore, relation estimating f_{st} from f_{cyl} is more useful.

Fig. 7.10 shows that, f_{st} increases with increasing f_{cyl}. Equations 7.22.1 and 7.22.2 are determined to represent the relation.

We may also investigate the other forms (see Section 3.3.4), but Eq. 7.22.1 (linear representation) is suitable (Table B.2) as a general relation between f_{st} and f_{cyl}.

7.3.3. Evaluation of Flexural Strength Test Results

In this study, the modulus of rupture was determined by center point loading on *100x100x500 mm* prisms on a span of *400 mm*.

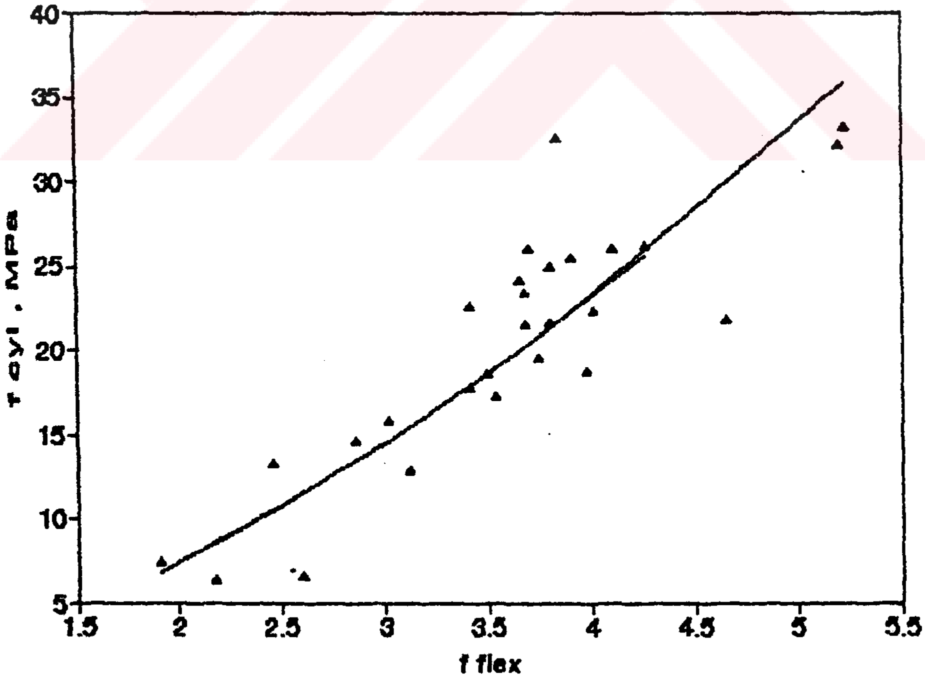


Fig. 7.11 Cylinder Compressive Strength versus Modulus of Rupture

THe relations between compressive strength and modulus of rupture using the forms cited in *Section 3.3.3*, are

$$f_{cyl}=2.394\ f_{flex}^{1.637} \qquad (7.23.1)$$

$$f_{flex}=0.8684 f_{cyl}^{0.4773} \qquad (7.23.2)$$

Table 7.7 Destructive Test Results

W/C	f_{cyl}	f_{c150}	f_{c200}	f_{st}	f_{flex}
SP 0.0%					
0.58	17.88	22.53	20.93	2.241	3.513
0.54	22.01	27.34	22.95	2.471	3.549
0.45	24.20	35.12	31.43	2.645	3.740
0.40	25.77	38.75	34.11	3.065	4.001
0.38	32.35	38.34	35.25	2.751	4.520
SP 0.5%					
0.58	19.11	24.58	21.39	2.541	3.860
0.45	26.08	35.24	31.69	2.827	3.978
0.38	33.18	41.26	35.84	3.253	5.825
SP 2.0%					
0.58	13.05	17.65	15.39	1.641	2.794
0.54	14.62	16.52	16.59	1.647	2.864
0.45	16.76	22.52	21.25	1.963	3.218
0.40	21.66	21.47	26.44	2.359	4.229
0.38	23.22	28.54	23.51	1.270	3.835
SP 5.0%					
0.58	6.81	8.31	7.69	0.831	2.044
0.45	6.51	10.96	8.62	0.959	2.606
0.38	0.43	1.72	0.90	0.132	1.325

The plot of experimental data in Fig. 7.11 shows that flexural strength increases at a decreasing rate with compressive strength. This leads to the choice of a power function form for the representation of the f_{cyl}-f_{flex} relation.

Equation 7.23.1 has correlation coefficient of r=96.83% (Table B.2), and the f-test result is suitable at α=0.01 level of significance (Table B.3).

7.4 EVALUATION OF NON-DESTRUCTIVE TEST RESULTS

7.4.1. Evaluation of Rebound Hammer Test Results

Empirical relationships (*Eq. 7.24 and 7.25*) were determined from Rebound numbers and strengths determined on cylindrical specimens. (Test results are given in *Table 7.8* as shown in *Fig. 7.12)*.

(See *Tables B2* and *B3* for statistical analysis of the equations.)

$$f_{cyl}=-5.3912+0.8106N_{cyl} \qquad (7.24)$$

$$f_{cyl}=0.001184\ N_{cyl}^{2.7906} \qquad (7.25)$$

Table 7.8 Rebound Hammer Test Results (km/s)

SP 0.0%

		150 mm Cube			200 mm Cube		
W/C	N_{cylR}	N_S	N_T	N_B	N_S	N_T	N_B
0.58	30.4	33.3	31.0	30.5	33.5	30.3	32.8
0.54	34.3	37.6	35.7	35.0	36.1	36.6	34.8
0.45	35.9	37.4	36.0	36.8	33.5	30.3	32.8
0.40	35.7	40.3	39.3	40.8	40.2	37.7	41.7
0.38	37.5	39.3	36.8	39.0	37.7	37.8	39.0

SP 0.5%

W/C	N_{cylR}	N_S	N_T	N_B	N_S	N_T	N_B
0.58	31.5	33.9	33.1	31.2	33.3	31.7	31.5
0.45	35.7	36.7	36.9	35.9	38.5	38.6	37.0
0.38	38.0	39.6	41.5	39.4	41.3	41.8	39.0

SP 2.0%

W/C	N_{cylR}	N_S	N_T	N_B	N_S	N_T	N_B
0.58	27.8	29.2	29.8	28.1	29.8	29.5	28.0
0.54	29.9	29.2	29.5	28.2	30.8	28.8	27.3
0.45	30.3	32.1	32.7	30.6	36.8	32.4	28.7
0.40	36.0	37.7	37.3	34.9	36.8	36.9	34.7
0.38	34.7	35.9	36.5	34.3	36.2	37.1	34.5

SP 5.0%

W/C	N_{cylR}	N_S	N_T	N_B	N_S	N_T	N_B
0.58	22.1	22.6	24.8	22.4	22.5	23.4	21.7
0.45	23.8	26.6	26.7	23.9	26.4	27.4	24.2
0.38	00.0	00.0	00.0	00.0	00.0	00.0	00.0

where N_S ≡ Rebound number of side of cube

N_T ≡ Rebound number of top of cube

N_B ≡ Rebound number of bottom of cube

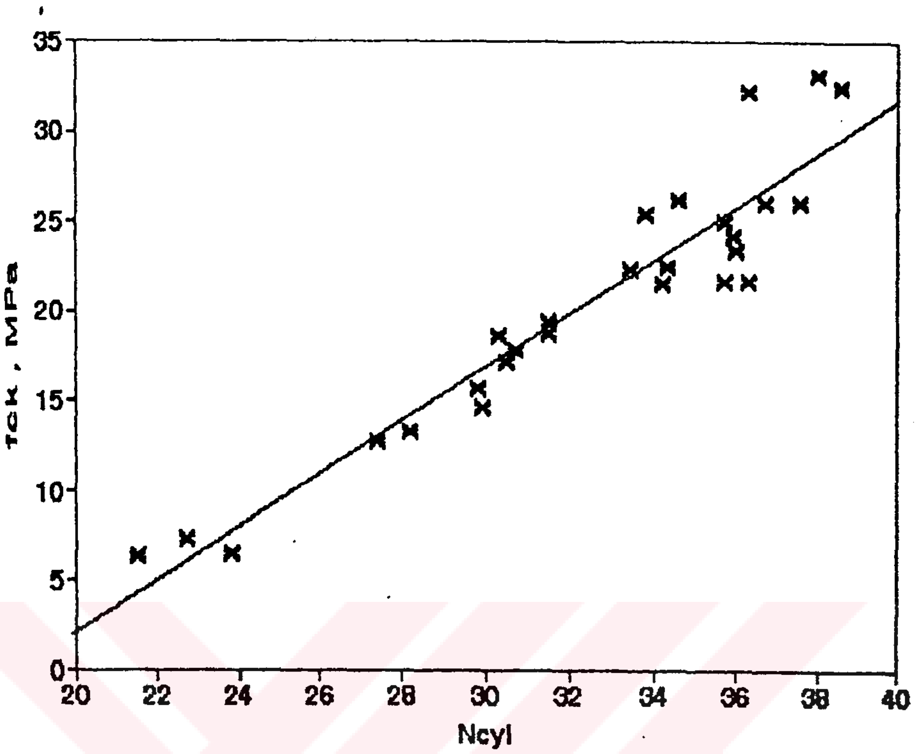


Fig. 7.12 Rebound Number N_{cyl} versus f_{cm} Relation Determined on 150 mm Diameter Cylinders and the experimental data points.

It is known that the rebound numbers give only a comparative result, if no direct calibration is carried out (Section 3.5.1).

Based on the experimental data obtained in this work (Section 7.1), Equations 7.24 and 7.25 were established. From Table B.2, is can be seen that

$$r_{Eq.7.25} = 0.963 > 0.779 = r_{Eq.7.24}$$

and

$$SSE_{Eq.7.25} = 141.97 < 469.78 = SSE_{Eq.7.24}$$

This shows that, within the scope of this work, power function form yields a better fit for the $f_{cyl}-N_{cyl}$ data.

7.4.2 Evaluation of Ultrasonic Pulse Velocity Test Results

Ultrasonic pulse velocities were calculated as the ratio of distance measured accurate to ± 0.5 mm to transit time accurate to 0.1 µs. Stastical analyses of the data given in *Table 7.9* yielded the relations.

$$f_{cyl}=0.00249 V_{cylR}^{5.97} \tag{7.26}$$

$$f_{cyl}=-14.2559 + 8 V_{cylR} \tag{7.27}$$

$$f_{cyl}=17.8205 - 19.7964 V_{cylR} + 4.6311 V_{cylR}^{2} \tag{7.28}$$

$$f_{cyl}=12.1787 - 12.5259 V_{cylR} + + 2.111 V_{cylR}^{2} + 0.2625 V_{cylR}^{3} \tag{7.29}$$

A plot of the data and the relations above can be seen in *Fig. 7.13*.

Table 7.9 *Ultrasonic Pulse Velocity Test Results in km/s*

			150 mm Cube		200 mm Cube	
SP 0.0%						
W/C	V_{cylR}	V_{cylA}	$V_{\perp}$	$V_{\parallel}$	$V_{\perp}$	$V_{\parallel}$
0.58	4.583	4.522	4.611	4.557	4.490	4.537
0.54	4.447	4.467	4.585	4.514	4.535	4.604
0.45	4.724	4.698	4.767	4.765	4.664	4.748
0.40	4.679	4.587	4.752	4.728	4.692	4.595
0.38	4.367	4.578	4.588	4.516	4.506	4.591
SP 0.5%						
0.58	4.574	4.576	4.568	4.581	4.583	4.535
0.45	4.690	4.653	4.774	4.778	4.582	4.656
0.38	4.830	4.602	4.752	4.760	4.668	4.619
SP 2.0%						
0.58	4.287	4.099	4.302	4.288	4.111	4.164
0.54	4.290	4.349	4.182	4.247	4.219	4.138
0.45	4.333	4.217	4.330	4.292	4.239	4.251
0.40	4.625	4.460	4.591	4.527	4.466	4.486
0.38	4.532	4.373	4.456	4.523	4.468	4.477
SP 5.0%						
0.58	3.735	3.610	3.791	3.851	3.653	3.672
0.45	3.861	3.658	3.904	3.893	3.879	3.815
0.38	1.798	1.251	1.508	1.554	1.179	1.072

where V_{cylR} ≡ Pulse velocity of cylinder specimens in the radial direction.

V_{cylA} ≡ Pulse velocity of cylinder specimens in the axial direction.

$V_{cu\perp}$ ≡ Pulse velocity of cube specimens measured in direction perpendicular to the direction of casting.

$V_{cu\parallel}$ ≡ Pulse velocity of cube specimens measured in directions parallel to the direction of casting.

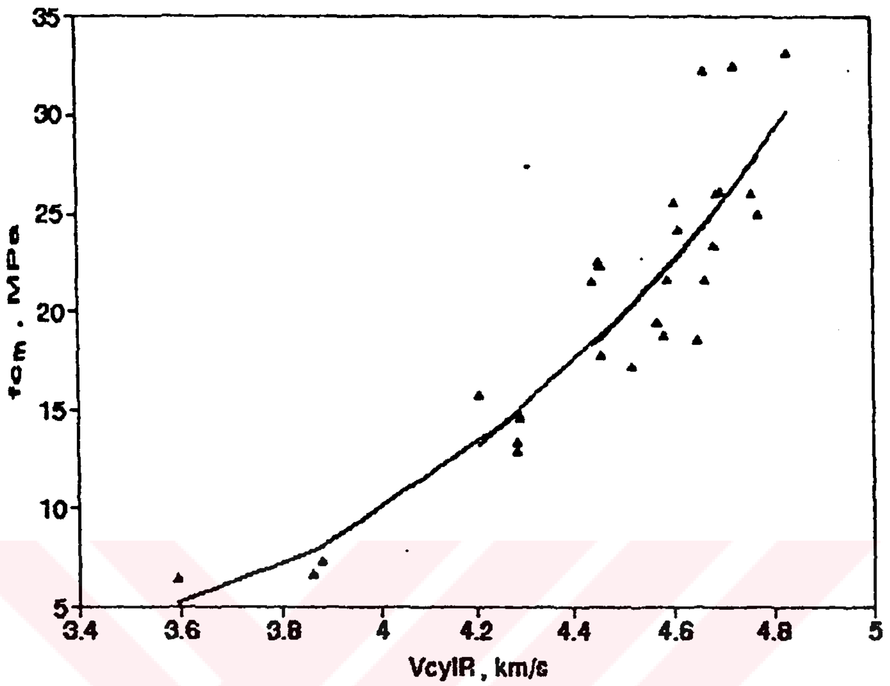


Fig. 7.13. Radial Pulse Velocity versus Compressive Strength of Cylinders at 28 Days from Eq. 7.26 and the experimental data points.

7.4.3 Combined Non-Destructive Evaluation

It is obviously possible to use more than one method at a time. This is advantageous when a variation in properties of concrete affects the test results in opposite directions. Such is the case with the presence of moisture in concrete: an increase in the moisture content results in an increase in the ultrasonic pulse velocity measured but decreases the rebound number recorded by the Schmidt hammer.

The combined empirical formulas for the estimation of cylinder strength are

$$f_{cyl}=10.7318-10.852V_{rad}+1.7743N_{cyl} \qquad (7.30)$$

$$\log f_{cyl}=-0.6364+0.2251V_{rad}+0.0285N_{cyl} \qquad (7.31)$$

$$f_{cyl}=e^{0.51838V_{rad}+0.06567N_{cyl}} \qquad (7.32)$$

$$f_{cyl}=0.001369\ V_{rad}^{1.2325}\ N_{cyl}^{2.2246} \qquad (7.33)$$

$$f_{cyl}=6.3385+1.4013N_{cube200S}-7.5657V_{cube200\perp} \qquad (7.34)$$

$$f_{cyl}=3.6897+1.2948N_{cube200S}-6.1130V_{cube200|} \qquad (7.35)$$

$$f_{cyl}=-1.1655+0.9300N_{cube200T}-2.0873V_{cube200\perp} \qquad (7.36)$$

$$f_{cyl}=-2.0588+0.8934N_{cube200T}-1.5971V_{cube200|} \qquad (7.37)$$

$$f_{cyl}=-1.9161+0.8109N_{cube200B}-0.8051V_{cube200\perp} \qquad (7.38)$$

$$f_{cyl}=-2.6459+0.7801N_{cube200B}-0.4084V_{cube200|} \qquad (7.39)$$

These relations can be used to estimate the strengths of in-situ concretes up to the age of 28 days with the accuracy specified in *Tables B2 and B3*. However, at later ages the accuracy will diminish in the unsafe direction primarily due to carbonation. Nevertheless, a comparative study of strengths can be made on concretes of similiar compositions made from the same cement and aggregate.

Linear, power, polynomial function forms to represent the relation of ultrasonic pulse velocity with compressive strength were investigated. Among these relations, Eq. 7.26, which is a power function, has the highest coefficient of correlation (r=89.3%), and Eq. 7.27 (linear) has the lowest (r=63.4%). Statistical analyses for the comparison of goodness of fit are given in Table B.2 and B.3. Although the coefficient of correlation increases up to 81%, there is no significant difference between the second and third degree polynomials (Eq. 7.28 and 7.29).

Two different non-destructive test results, rebound number and ultrasonic pulse velocity, are frequently used in combination to reduce the error in the estimation of in-situ concrete strength. Therefore combined relations were also investigated. Equations 7.30 through 7.33 are obtained from statistical analyses of cylinder test results, Equations 7.34 through 7.39 from cube test results. It may be concluded that, Eq. 7.32 (exponential function) gives the best fit. Nevertheless, the relations have statistical fit characteristics not significantly below those of Eq. 7.32.

This is due to the increased accuracy by the use of rebound number and pulse velocity results.

8. OPTIMIZATION

8.1. CONTROL STANDARD AND STANDARD DEVIATION

Standard deviation SD values are calculated by

$$SD(FCK, VM) = \frac{FCK \times VM}{1 - Z \times VM}$$

where, VM is coefficient of variation associated with the compressive strengths and Z is the percentile value corresponding to a specified level of confidence,

$$VM(FCK,CS)=FCS\times[1-SIGN(FCK-FCK0)\times(M/FCS)\times(FCK-FCK0)]$$

$$U(FCK-FCKO) = \begin{pmatrix} 0 & If & FCK \leq FCKO \\ 1 & If & FCK > FCKO \end{pmatrix}$$

$$FCS=0.0775+0.0225\times CS$$

where CS represents the control standard, and the FCK0 and the coefficients are determined based on experimental data collected by the Construction Materials Testing Laboratory of University of Gaziantep.

Coefficient of variation, VM, is assumed to be constant for FCK ≤ FCK0=40 MPa and, linearly decreasing with slope M=0.054348 %/MPa for FCK > FCK0. A plot of coefficient of variation versus characteristic strength for various control standards is given in *Fig. 8.1*.

In the Turkish standard TS 500 [32] Z score is taken as 1.28 for 90% level of confidence.

Table 8.1 Standard Deviation Values for Each Concrete Class

Standard Deviation of Characteristic Strengths (SD), MPa

fck Mpa	Quality Control Standard (CS)					
	Excellent 1	Very Good 2	Good 3	Fair 4	Poor 5	Very Poor 6
14	1.61	2.03	2.49	2.98	3.51	4.09
16	1.83	2.32	2.85	3.41	4.02	4.67
20	2.29	2.91	3.56	4.26	5.02	5.84
25	2.87	3.63	4.45	5.33	6.28	7.30
30	3.33	4.24	5.22	6.26	7.39	8.60
35	3.77	4.82	5.95	7.16	8.46	9.86

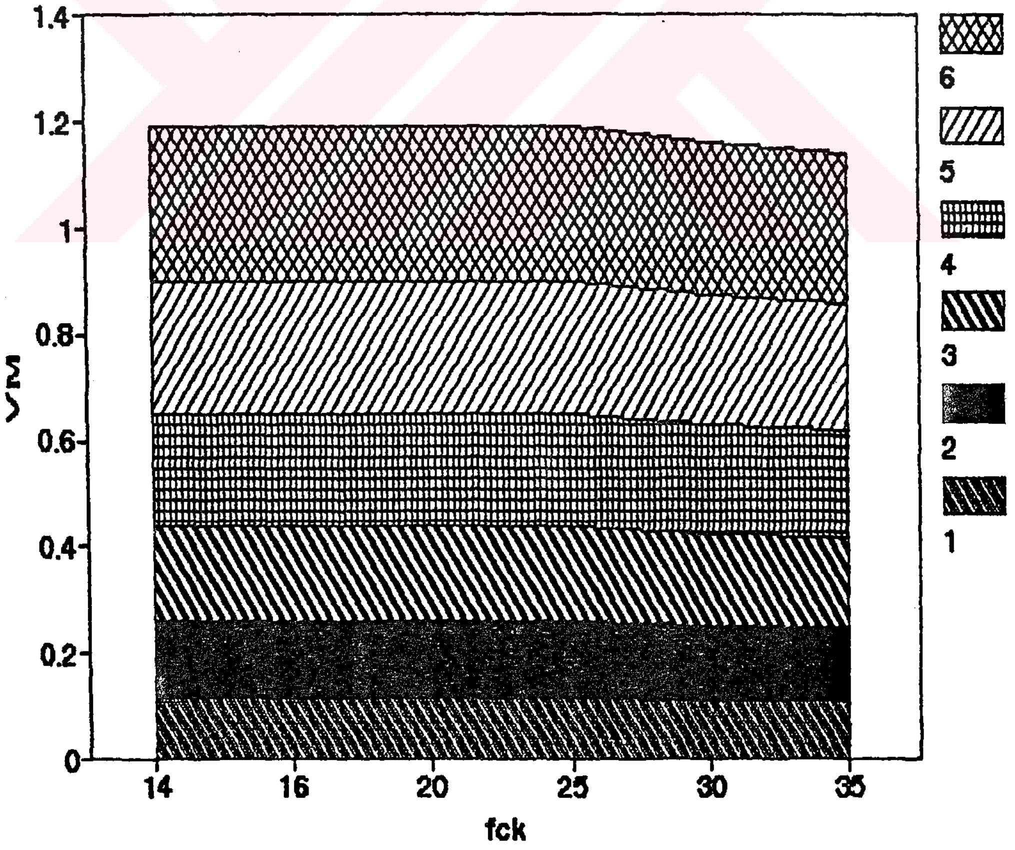


Fig 8.1 Coefficient of Variation versus f_{ck}

8.2. STRENGTH CONSTRAINT

In the computer program of the optimization model three alternative formula selections for the compressive strength, f are available;

$$f=\frac{f_{cc}}{K_G}\left(\frac{C}{W}\right)^2 \qquad \text{(Graff formula)}$$

$$f=\frac{f_{cc}}{K_{GM}}\left(\frac{C}{W+V_{air}}\right)^2 \qquad \text{(Modified Graff formula)}$$

$$f=K_F\left(\frac{C'}{C'+W'+V_{air}}\right)^2 \qquad \text{(Feret formula)}$$

and the constraint in the optimization model is,

$$f_{ca} = f_{ck} + Z \times SD \rightarrow f \geq f_{ca}$$

$$\boxed{f \geq f_{target}}$$

where K_G, K_{GM} and K_F are coefficients to be determined experimentally, f_{ck} is 28 day characteristic strength and, f_{ca} is 28 day target strength.

8.3 MINIMUM CEMENT CONTENT

Minimum cement content was determined as a function of the maximum size of aggregate, *D*, in mm from durability considerations using the empirical formula.

$$C_{min}=\frac{550}{\sqrt[5]{D}}$$

$$For\ D=31.5\ mm,\ C \geq 275\ kg\ C/m^3\ conc. \qquad (8.1)$$

8.4. WEIGHT AND VOLUME COMPATIBILITY CONDITIONS

Unit mass of concrete is equal to total mass of concrete constituents:

$$\sum_i X_i = W + SP + C + \sum_i A_i = \Delta \qquad (8.2)$$

Therefore, the sum of volumes of constituents should be equal to 1 m^3, hence

$$\sum_i \frac{X_i}{d_{X_i}} = \frac{W}{d_W}+\frac{SP}{d_{SP}}+\frac{C}{d_C}+\sum_i \frac{A_i}{d_{A_i}}+V_{air} = 1\ m^3 \qquad (8.3)$$

where W,SP,C and A_i ≡ Water, Superplasticizer, Cement and Aggregate mass respectively, kg/m^3 conc.

d_W, d_{SP}, d_C, d_{Ai} ≡ Densities of water, superplasticizer, cement and aggregates, kg/m^3

V_{air} ≡ Volume of air, m^3/m^3 conc.

Δ ≡ Mass of unit volume of fresh concrete, kg/m^3 conc.

Hence, with the numerical values

$$\frac{W}{999.4}+\frac{SP}{1198}+\frac{C}{2996}+\frac{A1}{2681}+\frac{A2}{2745}+\frac{A3}{2722}=1.0000-V_{air}$$

or

$$1.00060W+0.83472SP+0.33378C+$$
$$+0.37300A1+0.36430A2+0.36738A3=1000.0-1000V_{air}$$

Although any admixture, in small or large quantities, can be separately incorporated into the concrete mix design formulae, it is also possible to take it as part of the unhydrated cement. However, in this case the equivalent density of cement can be taken as

$$d_{ceq}=\frac{1+R_{sp}}{\frac{1}{d_C}+\frac{R_{sp}}{d_{SP}}}$$

and $C_{eq}=C+SP$ without altering the physical essence of the volume compatibility formulation.

For example, with $d_C=2996\ kg/m^3$ for superplasticizer dosage of $R_{sp}=0.75\%$ $d_{ceq}=2962.9\ kg/m^3$ for $R_{sp}=3.00\%$ $d_{ceq}=2870.5\ kg/m^3$.

8.5. WORKABILITY

In this study, a more realistic water requirement formula was experimentally developed by taking into consideration the slump and superplasticizer content. The water requirement for *0.0% superplasticizer* content was written as

$$W_0=0.1119C+(0.11874-0.0204k_{As})\Sigma A+$$
$$+82.59+1.015\ S-0.00608\ S^2+1.37x10^{-5}\ S^3$$

where k_{A9} fineness modulus of combined aggregate when a nine-sieve set with the smallest size 0.125 mm mesh is used. $k_{A9} \approx 5.2$ for the aggregate grading used in this work, and S is the (Abrams cone) slump in mm.

The water requirement W of a concrete mix to which a superplasticizer is added was estimated by

$$W = W0\ (1 - WR)$$

where the water reduction function, WR, was expressed as a function of the superplasticizer dosage R_{sp} by

$$WR(R_{sp}) = r_\infty [1 - e^{(-m_0 R_{sp})}] \qquad (8.4)$$

Here R_{sp} ≡ Superplasticizer dosage by weight ratio of cement

WR ≡ Water reduction function.

r_∞, m_0 ≡ Coefficients to be determined experimentally

Typical values of r_∞ and m_0 are given for various W/C ratios in *Table 8.2.*

Table 8.2 Typical Values of the Coefficients r_∞ and m_0 in Eq. 8.4

NOMINAL CONCRETE CLASS	W/C	r_∞	m_0	Initial Slope $r_\infty{}^* m_0$
C 14	0.58	0.215	80.9	17.4
C 16	0.54	0.279	60.6	16.9
C 20	0.45	0.376	110.4	41.5
C 25	0.40	0.284	80.4	22.8
C 30	0.38	0.278	105.0	29.2

8.6. GRADING AND PUMPABILITY CONSTRAINTS

The grading of the pumpable concrete mix, P_{dj}, enforces two sets of limits in the grading zone,

$P_{dj,low} \leq P_{dj} \leq P_{dj,up}$.

For pumpability, more specific upper and lower grading limits were written as $0.77 \leq P_{16} \leq 0.81$ and $0.27 \leq P_{0.5} \leq 0.32$. From these inequalities:

$$\boxed{\begin{array}{c} -0.90646C - 1.01296A1 - 0.98934A2 + 2.75556A3 \geq 0 \\ 0.90646C + 0.29714A1 - 0.31659A2 - 0.32991A3 \geq 0 \\ A1 \geq 0 \\ A2 \geq 0 \\ A3 \geq 0 \end{array}}$$

upper and lower limits were obtained.

8.7. OBJECTIVE FUNCTION

Unit prices for each ingredient and quality control costs were converted to relative quantities by mass of *KÇ 325* cement.

Table 8.3 Relative Costs of Materials (RCM)

Material	WATER	SP	KÇ32.5	FINE AGG.	MEDIUM AGG.	COARSE AGG.
Relative Costs, 10^{-2}rcu	0.358	1500	100	7.267	4.748	4.748

1 rcu = 1 relative cost unit = 1 kgC/kg material

$$RTCM = [0.358W + 1500SP + 100C + 7.267\,A1 + 4.748\,(A2+A3)] \times 10^{-2}$$

where RTCM ≡ Relative total cost of component materials of concrete.

8.8. COST OF QUALITY CONTROL

Cost of quality control was estimated from the cost of tests (laboratory and field) and/or wages of personnel in charge of quality control, cost of any expert service provided and the capital cost of quality control equipment. This cost was assumed to be dependent on the quality standard, *QC*, and independent of slump and class of concrete, as shown in *Table 8.4*.

Table 8.4 Relative Cost of Quality Control (RCQC)

L^* CONTROL STAN.	EXCELLENT 1	VERY GOOD 2	GOOD 3	FAIR 4	POOR 5	VERY POOR 6
RCQC, kgC	45.2	33.6	24.9	14.7	2.4	0.5

L^* ≡ Number corresponding to the specified control standard

8.9. COST OF TRANSPORTATION, PLACING, PUMPING AND COMPACTION

For calculating cost of compaction, CC, as a function of slump, S, an empirical exponential formula [11, p 37] expressed as

$$\boxed{CC(S) = (1.10+1.0535\ e^{-0.01946\ S})}$$

was used, where CC(S), is the cost of compaction as a function of slump, S and 50 mm ≤ S ≤ 200 mm based on the assumption that the cost of workmanship and energy of compaction operation for $S=140$ *mm* is *0.25 kgC/m^3 conc.*, requiring only spreading but no vibration, and the capital cost of compaction equipment is *1.10 kgC/m^3 conc.*

Cost of transportation and placing was taken as the sum of cost of transportation on transmixers to an average distance of 10 km and cost of pumping 16 m vertically and 16 m horizontally.

Similar relation was used for estimating the cost of placing (transporting and/or pumping to the point where the concrete will be cast).

$$\boxed{CP(S) = (8.718+0.8348\ e^{-0.01946S})}$$

where CP(S) is the cost of transporting and placing as a function of slump, assuming that $0.25/1.35=0.185=18.5\%$ of 10.70 rcu of total relative cost of placing, and 1.979 rcu is the cost of workmanship and energy and the remaining $0.815x10.70 = 8.718$ *rcu* is the capital cost of transporting and pumping.

The total cost of Placing and Compaction (TCPC) was then taken as $TCPC(S) = CC(S) + CP(S)$

$$\boxed{TCPC(S) = (9.818 + 1.8883 e^{-0.01946S})}$$

8.10. COST OF FORMWORK AND SCAFFOLDING

A maximum formwork cost of 217817 TL/m^2 was associated with *Point A corresponding to 0 mm slump Fig. 8.2,* the highest formwork cost in the list of unit prices. A minimum cost of 38850 TL/m^2 was associated with a slump of 175 mm the average initial slump of pumped concrete in the market (based on 1994 unit cost lists by the Ministry of Public Works).

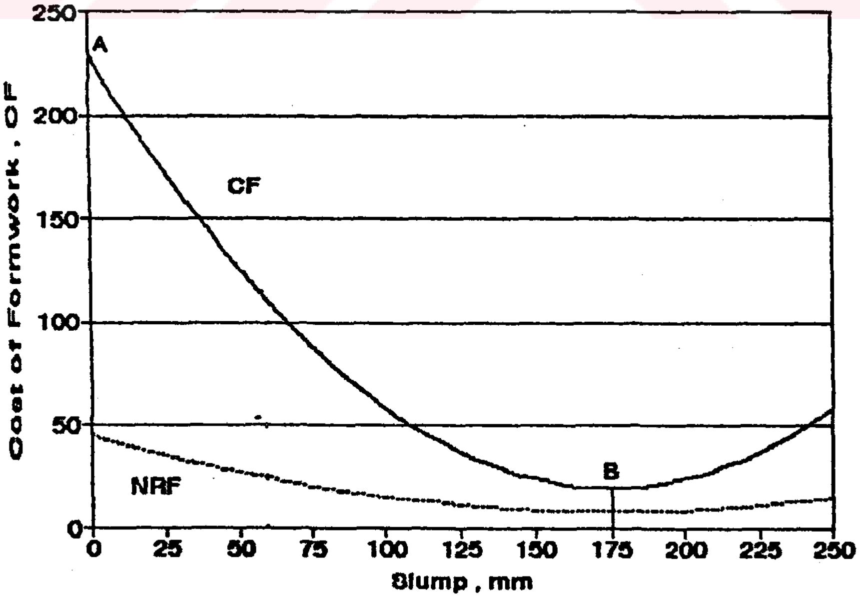


Fig. 8.2 The Slump versus Cost of Formwork

A second degree parabolic relation

$$CF1=217817 - 2045.34S + 5.84382S^2 \quad TL/m^2 \qquad (8.5)$$

was thus established. The maximum cost of 107900 TL/m^2 of lumber for formwork was taken as the highest cost in the list of unit prices [19]. The minimum cost 20790 TL/m^2 was associated with a slump of 175 mm and second degree parabolic relation

$$CLF=107900 - 995.543S + 2.8444S^2 \quad TL/m^2 \qquad (8.6)$$

was adopted. This relation comprises an increase in cost of lumber for formwork for slumps higher than 175 mm as does the CF1 relation, taking into account an increase in the extra pressure exerted on formwork by concretes of higher fluidity.

In determining the number of reuses of formwork, NRF, the maximum numbers was assumed to be 24 for S=0 mm slump for the most expensive formwork, and the minimum number was taken to be 8 for S=175 mm.

$$NRF=24 - 1.123x10^{-3}S + 3.2087x10^{-6}S^2 \qquad (8.7)$$

$$CF=CF1 - CLF\left(1-\frac{1}{NRF}\right) \quad TL/m^2 \qquad (8.8)$$

The cost of scaffolding was assumed not to vary with slump. Relative cost of scaffolding was not taken into account as an optimization variable in the simplex algorithm but is included in the relative total cost as a function of the storey height of the building.

Unit cost of scaffolding (CS1) and cost of lumber for scaffolding (CLS) for different storey heights was determined from the price lists published by the Ministry of Public Works and Housing, and an average number of reuses of scaffolding was taken as 15 throughout in determining the optimum concrete from the ready-mixed concrete producers' point of view. It is to be noted that the ready-mixed concrete producers in Gaziantep undertake the compaction of concrete as well.

The cost of scaffolding is, therefore,

$$CS = CS1 - CLS \times (1-\frac{1}{NRF})$$

and total cost of formwork and scaffolding.

$$\boxed{CFS=(CF + CS \times H) \times \frac{AF}{CC}}$$

where CFS ≡ Relative cost of formwork and scaffolding per cubic meter of concrete, kg C/m^3 conc.

AF ≡ Amount of formwork per unit volume of concrete, m^2/m^3 concrete

Based on analysis carried out on various types of buildings, at levels starting from basement up to top, it was seen the value of **AF** varied between *5* and *10.5* m^2/m^3 *conc.* [12]. Therefore, an average value was taken as

$7\ m^2/m^3$ conc. for the purpose of this work.

From these formulas Relative Total Cost function was obtained as

$$\boxed{RTC = \left(\begin{array}{c} RTCM + RCQC + TCPC + CFS + \\ + (\text{Cost of Mixing} + \text{Cost of Administration} + \\ + \text{Cost of Capital for the central plant}) \end{array} \right)}$$

by summing the cost corresponding to materials, control standard, mixing, transportation, placing and compaction, administration, capital, formwork and scaffolding.

However, the partial sum of costs of administration and capital was assumed not to vary with the mix parameters and therefore taken as constants in the optimization model (*see Appendix E*).

8.11. DISCUSSION ON THE CHOICE OF OBJECTIVE FUNCTION

It should be kept in mind that costs of critical pieces of equipment, an increase in the capital cost of for instance pump, or vibrators, may result in an increase in the workmanship or operating costs per cubic metre of concrete. An optimum combination of all components may, therefore, vary from job to job depending on the total volume of concrete, the distances to which the concrete is to be transported, conveyed and/or pumped, the compactive energy of the vibrators etc.

8.12. DESCRIPTION OF THE CHARACTERS USED IN THE PROGRAM

The characters or variables used in the computer program are as follows:

RCQC ≡ Relative cost of quality control, kgC/m^3

FCK ≡ Characteristic strength, MPa

IW ≡ Number of constraints, *15*

IX ≡ Number of real variables, *6*

IG ≡ Number of ***greater thans*** ($>$ or $\geq$), *13*

NEQ ≡ Number of equalities, *2*

IL ≡ Number of ***less thans*** ($<$ or $\leq$), *0*

SL ≡ Slump, mm

SP ≡ Superplasticizer content, %

CFS ≡ Cost of formwork and Scaffolding, kgC/m^3 conc.

AF ≡ Amount of formwork m^2/m^3 conc.

CF ≡ Cost of formwork, kgC/m^3 conc.

CF1 ≡ Cost of formwork, TL/m^2 conc.

CC ≡ Cost of cement, TL/kgC

NRS ≡ Number of reuses of scaffolding

CS ≡ Cost of scaffolding kgC/m^3 conc.

H ≡ Storey height, m

CS1 ≡ Cost of scaffolding, TL/m^2 formwork

CLS ≡ Cost of lumber of scaffolding, TL/m^2 formwork

CFS ≡ Relative cost of formwork and scaff., kgC/m^3 conc.

NRF ≡ Number of reuses of formwork

CLF ≡ Cost of lumber of formwork, TL/m^2 formwork

RTMX ≡ Maximum value (dummy)

IQ ≡ Number of slump values

MM ≡ Number of characteristic strength

IJ ≡ Number of superplasticizer dosage

KK ≡ Number of control standard

MEN ≡ Admixture menu's control parameter

MEN2 ≡ Strength menu's control parameter

SD ≡ Standard deviation of compressive strength, MPa

WR ≡ Water reduction factor, kg_W/kg_{WO}

VA ≡ Air content volume, %

CF ≡ Feret coefficient

CG ≡ Graff coefficient

CMG ≡ Modified Graff coefficient

TC ≡ Total cost, kgC/m^3 conc.

TCPC ≡ Total cost of placing and compaction, kgC/m^3 conc.

RTC ≡ Relative total cost, kgC/m^3 conc.

8.13. LINEAR OPTIMIZATION AND SIMPLEX ALGORITHM

In an *optimization problem*, the objective is to *optimize* (*maximize* or *minimize*) some function *f*. This function *f* is called the ***objective function***.

For example, an objective function *f* to be *maximized* may be the revenue in a production of TV sets, the yield per minute in a chemical process, the mileage per gallon of a certain type of car, the hourly number of customers served in some office, the hardness of steel or the tensile strength of a rope.

Similarly, we may want to *minimize f*, the cost per unit quantity of production of certain concrete, the operating cost of some ready-mixed concrete plant, the daily loss of heat in a heating system, the idling time of some concrete pump, the time needed to produce a storey of a building or as in this work, cost of concrete.

In most optimization problems the objective function *f* depends on several variables $(x_1,......,x_n)$. These are called ***control variables*** because we can "control" them, that is, choose their values. For example, the yield of a chemical process may depend on pressure x_1 and temperature x_2.

Optimization theory develops methods for optimal choices of $x_1,......,x_n$, which maximize (or minimize) the objective function *f*, that is, methods for finding optimal values of $x_1,......,x_n$.

In many problems the choice of values of $x_1,......,x_n$ is not entirely free but is subject to some ***constraints***, that is, additional conditions arising from the nature of the problem and the variables.

Linear Programming (or ***linear optimization***) consists of methods for solving optimization problems in which the objective function *f* is a *linear* function of the control variables $x_1,......,x_n$, and the domain of these variables is restricted by a system of linear inequalities.

Problems of this type arise frequently, for instance in production, distribution or transportation of goods, economics and approximation theory.

Setting up the Problem

Let us consider a problem consisting the production of tables and chairs where the algebraic statement of the problem is:

Maximize: Profit=8T+6C

Subject to: Assembly $4T + 2C \le 60$, Finishing $2T + 4C \le 48$ and $T, C \ge 0$.

Before the simplex method can be used to solve a linear program, all the inequality constraints must first be converted to equations. This is done by adding to each of the $\le$ inequality constraints a variable which measures the *slack time*, that is, the "left over" in each department after the tables and chairs are manufactured. These new variables are called *slack variables*, and the original variables in the problem are called *decision variables* (or *structural variables*). To illustrate this process, let S_A ≡ slack variable (unused time) in assembly and

S_F ≡ slack variable (unused time) in finishing.

S_A is equal to the amount of time available in assembly (60 hours) less any hours used there in processing tables and chairs. S_F is equal to the total amount of time available in finishing (48 hours) less any hours used there in processing tables and chairs. We can express these two statements in mathematical form by writing equations for the slack variables S_A and S_F as follows:

Assembly $S_A = 60 - 4T - 2C$ and

Finishing $S_F = 48 - 2T - 4C$

By adding the slack variables. we convert the *constraints inequalities* in the problem into *equations*. The slack variable in each department takes on whatever value is required to make the equation relationship hold. Two examples will clarify this point.

Assume that in assembly T=5 and C=3, S_A=34 hr unused time

Assume that in finishing T=4 and C=6, S_F=16 hr unused time.

By adding a slack variable to each inequality, we convert them into these equations:

$$4T + 2C + S_A = 60$$

$$2T + 4C + S_F = 48$$

In the simplex method, variables which do not affect an equation are written with zero coefficient. For example, since S_A and S_F represent unused time which yields no profit, these variables are added to the objective function with zero coefficients. Furthermore, since S_A represents unused time in assembly only, it is added to the equation representing finishing with a zero coefficient. For the same reason $0S_F$ .is added to the equation representing the time constraints in assembly. Thus this problem, in its final form is

Maximize : Profit $= 8T + 6C + 0S_A + 0S_F$

Subject to: $4T + 2C + S_A + 0S_F = 60$

$2T + 4C + 0S_A + S_F = 48$

$T, C, S_A, S_F \geq 0$

Let us a minimization problem also.

Minimize: Cost $= 20T + 8C$

Subject to: Assembly: $4T + 2C \leq 60$

Finishing: $2T + 4C \leq 48$

Min. # of tables : $T \geq 2$

Min. # of chairs : $C \geq 4$

$T, C \geq 0$

In order to convert the last two constraints into equations, we *subtract* from each of them variables which measure the *surplus* numbers of tables and chairs made above and beyond the minimum numbers required. These new variables are another type of slack variable like those we previously used to convert less-than-or-equal-to constraints to equations. The slack variables subtracted from greater-than-or-equal-to constraints to convert them to equations are often referred to as ***surplus variables***. To illustrate surplus variables, let

$S_T = T - 2 =$ Surplus tables

$S_C = C - 4 =$ Surplus chairs

Thus if 11 tables and 8 chairs are made. the surplus variables are

$$S_T = 11 - 2 = 9 \text{ Surplus tables}$$

$$S_C = 8 - 4 = 4 \text{ Surplus chairs}$$

Just as with slack variables, surplus variables do not affect the objective function or the other constraints, so they are added in the there with zero coefficients. This problem in final form:

Minimize: $\text{Cost} = 20T + 8C + 0S_A + 0S_F + 0S_T + 0S_C$

Subject to: $T, C \geq 0$

$$4T + 2C + S_A + 0S_F + 0S_T + 0S_C = 60$$

$$2T + 4C + 0S_A + S_F + 0S_T + 0S_C = 48$$

$$T + 0C + 0S_A + 0S_F - S_T + 0S_C = 2$$

$$0T + C + 0S_A + 0S_F + 0S_T - S_C = 4$$

The solution method of this optimization equalities by simplex method is shown by Levin et al. [8, pp 386-ff] simply.

8.14. SETTING UP OF THE INITIAL SIMPLEX TABLEAU FOR COMPUTER PROGRAM AND THE OUTPUTS

8.14.1 The Initial Simplex Tableau

Using constructed constraints of this work and optimization technique, the computer program was written and initial simplex table, results of this program is shown in following pages. List of the computer program and its flow chart are given in **Appendix D**.

8.14.2 The Outputs of the Computer Programme

The computer program reads the initial tableau (*Table 8.5*) from an input file and designs a concrete mix with minimum cost satisfying the strength, workability and volume compatibility conditions by the Simplex algorithm with known

- costs of materials
- characteristic strength
- slump
- admixture dosage
- air content
- control standard
    - standard deviation
    - cost of quality control

Then, in each characteristic strength for each slump and admixture content, chooses the mix with minimum cost noting also the level of control standard associated with it and *Tables 8.6.1, 8.6.4 and 8.6.7* are obtained by running the program taking into account the cost of materials and quality control. *Tables 8.6.2, 8.6.5 and 8.6.8* are results of optimization in which cost of compaction also was included. The results given in Tables *8.6.3, 8.6.6 and 8.6.9* include the cost of formwork and scaffolding. To these costs, the sum of general cost of mixing (76.93 kgC/m^3 conc.), management (7.034 kgC/m^3 conc.) and placing-compaction (2.962 kgC/m^3 conc.) and gross profit of 7% to reflect net growth should be added.

Table 8:5 Initial Simplex Tableau

Conditions		Coefficients of Constraints							
		C	W	A1	A2	A3	SP		
Durability		1	0	0	0	0	0	≥	275
Strength		1^*	0^*	0	0	0	0	≥	0^*
Aggregates Requirements		0	0	1	0	0	0	≥	0
		0	0	0	1	0	0	≥	0
		0	0	0	0	1	0	≥	0
Workability		-0.112^*	1	-0.017^*	-0.017^*	-0.017^*	0	≥	0^*
Grading Limits	16mm	-0.906	0	-1.013	-0.989	2.756	0	≥	0
	8mm	-0.906	0	-1.013	0.669	1.907	0	≥	0
	2mm	-0.906	0	-0.350	0.784	0.809	0	≥	0
	1mm	0.906	0	0.352	0.427	-0.442	0	≥	0
	0.5mm	0.906	0	0.297	0.317	-0.330	0	≥	0
	0.25mm	0.906	0	0.013	0.242	-0.248	0	≥	0
	0.125mm	0.906	0	0.119	0.173	-0.175	0	≥	0
SP		1	0	0	0	0	-1	≥	0
Volumetric		0.333^*	1	0.373	0.364	0.367	0.835	≥	0^*

** : Recomputed and changed by the computer program primarily in compliance with the workability and durability requirements*

8.15 THE USE OF OPTIMUM MIX TABLES

To choose an optimum concrete mix, these tables of minimum costs should be used in conjunction with a corresponding list of compositions as shown in *Appendix D*. An example of an optimum solution is given in Fig. 8.2.

Class of concrete is usually dictated by the requirements of project, workability should comply with the means of compaction available, and the control standard should be in accordance with the project requirements and related facilities.

Table 8.6.1 CS and RTC Using The Graff Strength Formula Excluding Cost of Placing and Compaction

		Slump , mm															
		50		60		80		100		125		150		175		200	
fck MPa	SP %	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	**525**	**5**	**531**	**5**	**541**	**5**	**548**	**5**	**554**	**5**	**558**	**5**	**562**	**5**	**568**	**5**
	0.25	532	5	535	5	546	5	553	5	559	5	563	5	567	5	574	5
	0.50	548	5	550	5	555	5	563	5	569	5	573	5	578	5	584	5
	0.75	569	5	569	5	574	5	578	5	585	5	590	5	595	5	602	5
	1.00	591	5	591	5	596	5	601	5	608	5	613	5	619	5	626	5
	1.25	615	5	616	5	624	5	631	5	639	5	645	5	651	5	659	5
	1.50	641	5	647	5	659	5	669	5	678	5	685	5	691	5	701	5
	1.75	677	5	687	5	704	5	716	5	726	5	733	5	741	5	751	2
	2.00	726	5	738	5	757	2	770	2	780	2	788	2	796	2	807	2
16	0.00	**547**	**5**	**554**	**5**	**565**	**5**	**573**	**5**	**579**	**5**	**584**	**5**	**588**	**5**	**595**	**5**
	0.25	551	5	558	5	570	5	578	5	584	5	589	5	594	5	601	5
	0.50	560	5	567	5	579	5	587	5	594	5	599	5	604	5	611	5
	0.75	579	5	582	5	595	5	603	5	610	5	616	5	621	5	629	5
	1.00	600	5	605	5	617	5	626	5	634	5	639	5	645	5	654	5
	1.25	626	5	632	5	646	5	657	5	665	5	671	5	678	5	687	5
	1.50	658	5	667	5	684	5	695	5	705	5	712	5	719	5	729	5
	1.75	699	5	711	5	729	5	742	5	752	2	759	2	767	2	777	2
	2.00	749	2	761	2	781	2	794	2	805	2	813	2	822	2	834	2
18	0.00	**569**	**5**	**577**	**5**	**589**	**5**	**597**	**5**	**604**	**5**	**609**	**5**	**614**	**5**	**622**	**5**
	0.25	573	5	581	5	593	5	602	5	609	5	614	5	619	5	627	5
	0.50	582	5	591	5	603	5	612	5	620	5	625	5	630	5	638	5
	0.75	598	5	606	5	620	5	629	5	637	5	643	5	648	5	657	5
	1.00	620	5	629	5	644	5	654	5	662	5	668	5	674	5	684	5
	1.25	649	5	659	5	675	5	686	5	696	5	702	5	709	5	719	5
	1.50	687	5	698	5	716	5	728	5	738	5	745	2	753	2	763	2
	1.75	732	5	745	2	763	2	776	2	787	2	795	2	803	2	814	2
	2.00	783	2	797	2	818	2	832	2	844	2	853	1	862	1	874	1
20	0.00	590	5	598	5	611	5	620	5	628	5	633	5	638	5	647	5
	0.25	575	5	583	5	595	5	604	5	611	5	616	5	621	5	629	5
	0.50	**570**	**5**	**577**	**5**	**590**	**5**	**598**	**5**	**605**	**5**	**610**	**5**	**615**	**5**	**623**	**5**
	0.75	583	5	587	5	593	5	602	5	609	5	614	5	620	5	627	5
	1.00	606	6	606	5	611	5	616	5	623	5	628	5	634	5	642	5
	1.25	630	6	630	6	634	5	639	5	645	5	651	5	657	5	666	5
	1.50	655	6	655	5	662	5	668	5	677	5	684	5	690	5	700	5
	1.75	680	5	685	5	696	5	708	5	718	5	725	5	732	5	743	5
	2.00	716	5	724	5	743	5	756	2	767	2	774	2	782	2	793	2
25	0.00	642	5	651	5	667	5	677	5	686	5	692	5	699	5	708	2
	0.25	**640**	**5**	**649**	**5**	**665**	**5**	**675**	**5**	**684**	**5**	**690**	**5**	**697**	**5**	**707**	**5**
	0.50	645	5	655	5	671	5	682	5	691	5	697	5	704	5	714	5
	0.75	660	5	670	5	687	5	698	5	707	5	714	5	721	5	731	2
	1.00	683	5	694	5	712	5	724	5	734	2	741	2	748	2	758	2
	1.25	716	5	729	5	747	2	759	2	769	2	777	2	784	2	795	2
	1.50	758	2	770	2	790	2	804	2	815	2	823	2	832	2	844	1
	1.75	808	2	822	2	844	1	859	1	871	1	880	1	889	1	903	1
	2.00	867	1	883	1	907	1	924	1	938	1	948	1	958	1	973	1
30	0.00	690	5	702	2	717	2	729	2	738	2	745	2	751	2	761	2
	0.25	**681**	**5**	**691**	**5**	**708**	**5**	**719**	**2**	**729**	**2**	**735**	**2**	**742**	**5**	**752**	**2**
	0.50	682	5	693	5	710	5	722	2	731	2	738	2	745	2	754	2
	0.75	694	5	706	5	724	5	735	2	745	2	752	2	759	2	769	2
	1.00	718	5	731	5	748	2	761	2	771	2	778	2	786	2	797	2
	1.25	753	2	765	2	784	2	798	2	809	2	817	2	825	2	837	2
	1.50	797	2	811	2	832	2	847	1	859	1	868	1	877	1	890	1
	1.75	853	1	868	1	891	1	908	1	921	1	931	1	941	1	956	1
	2.00	919	1	936	1	963	1	981	1	996	1	008	1	019	1	035	1

Table 8.6.2 CS and RTC Using The Graff Strength Formula Including Cost of Placing and Compaction.

		Slump, mm															
		50		60		80		100		125		150		175		200	
fck MPa	SP %	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	535	5	541	5	551	5	558	5	564	5	568	5	572	5	578	5
	0.25	542	5	546	5	556	5	563	5	569	5	573	5	577	5	583	5
	0.50	559	5	561	5	565	5	573	5	579	5	583	5	588	5	594	5
	0.75	580	5	579	5	584	5	588	5	595	5	600	5	604	5	612	5
	1.00	602	5	602	5	607	5	611	5	618	5	623	5	629	5	636	5
	1.25	626	5	626	5	634	5	641	5	649	5	655	5	661	5	669	5
	1.50	652	5	658	5	669	5	679	5	688	5	695	5	701	5	711	5
	1.75	688	5	697	5	714	5	726	5	736	5	743	5	751	5	761	2
	2.00	739	5	749	5	767	2	780	2	790	2	798	2	806	2	817	2
16	0.00	558	5	564	5	575	5	583	5	589	5	593	5	598	5	605	5
	0.25	562	5	569	5	580	5	588	5	594	5	599	5	603	5	610	5
	0.50	571	5	578	5	589	5	597	5	604	5	609	5	614	5	621	5
	0.75	589	5	593	5	605	5	613	5	620	5	626	5	631	5	639	5
	1.00	611	5	615	5	627	5	636	5	644	5	649	5	655	5	663	5
	1.25	637	5	642	5	657	5	667	5	675	5	681	5	688	5	697	5
	1.50	668	5	678	5	694	5	705	5	715	5	721	5	728	5	739	5
	1.75	710	5	721	5	740	5	752	5	762	2	769	2	777	2	787	2
	2.00	759	2	772	2	791	2	804	2	815	2	823	2	831	2	843	2
18	0.00	580	5	587	5	599	5	607	5	614	5	619	5	624	5	632	5
	0.25	584	5	592	5	604	5	612	5	619	5	624	5	629	5	637	5
	0.50	593	5	601	5	614	5	622	5	630	5	635	5	640	5	648	5
	0.75	608	5	617	5	630	5	639	5	647	5	653	5	658	5	667	5
	1.00	630	5	639	5	654	5	664	5	672	5	678	5	684	5	693	5
	1.25	660	5	670	5	686	5	697	5	706	5	712	5	719	5	729	5
	1.50	697	5	708	5	726	5	738	5	748	5	755	2	762	2	773	2
	1.75	743	5	755	2	774	2	786	2	797	2	805	2	813	2	824	2
	2.00	794	2	807	2	828	2	842	2	854	2	863	1	872	1	884	1
20	0.00	600	5	609	5	621	5	630	5	638	5	643	5	648	5	656	5
	0.25	585	5	593	5	605	5	614	5	621	5	626	5	631	5	639	5
	0.50	580	5	588	5	600	5	608	5	615	5	620	5	625	5	633	5
	0.75	594	5	597	5	604	5	612	5	619	5	624	5	630	5	637	5
	1.00	616	6	616	5	621	5	626	5	633	5	638	5	644	5	652	5
	1.25	640	6	640	6	644	5	649	5	655	5	661	5	667	5	676	5
	1.50	665	6	665	5	672	5	678	5	687	5	693	5	700	5	710	5
	1.75	691	5	696	5	706	5	718	5	728	5	735	5	742	5	753	5
	2.00	727	5	735	5	754	5	767	2	777	2	784	2	792	2	803	2
25	0.00	652	5	662	5	677	5	687	5	696	5	702	5	709	5	718	2
	0.25	650	5	660	5	675	5	685	5	694	5	700	5	707	5	716	5
	0.50	656	5	666	5	681	5	692	5	701	5	707	5	714	5	724	5
	0.75	670	5	681	5	697	5	708	5	717	5	724	5	731	5	741	2
	1.00	694	5	705	5	722	5	734	5	744	2	751	2	758	2	768	2
	1.25	727	5	739	5	757	2	769	2	779	2	787	2	794	2	805	2
	1.50	768	2	781	2	800	2	814	2	825	2	833	2	842	2	854	1
	1.75	818	2	832	2	854	1	869	1	881	1	890	1	899	1	913	1
	2.00	878	1	893	1	917	1	934	1	948	1	958	1	968	1	983	1
30	0.00	701	5	712	2	728	2	739	2	748	2	754	2	761	2	771	2
	0.25	691	5	701	5	718	5	730	2	739	2	745	2	752	5	762	2
	0.50	692	5	703	5	720	5	732	2	741	2	748	2	754	2	764	2
	0.75	705	5	716	5	734	5	746	2	755	2	762	2	769	2	779	2
	1.00	729	5	741	5	759	2	771	2	781	2	788	2	796	2	807	2
	1.25	763	2	775	2	795	2	808	2	819	2	827	2	835	2	847	2
	1.50	808	2	821	2	843	2	857	1	869	1	878	1	887	1	900	1
	1.75	863	1	878	1	902	1	918	1	931	1	941	1	951	1	966	1
	2.00	930	1	947	1	973	1	991	1	006	1	017	1	029	1	045	1

Table 8.6.3 ,CS and RTC Using The Graff Strength Formula Including Cost of Formwork and Scaffolding

Slump , mm

fck MPa	SP %	50		60		80		100		125		150		175		200	
		RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	845	5	851	5	861	5	868	5	873	5	877	5	882	5	888	5
	0.25	852	5	856	5	866	5	873	5	878	5	883	5	887	5	893	5
	0.50	869	5	870	5	875	5	882	5	888	5	893	5	897	5	904	5
	0.75	889	5	889	5	894	5	898	5	905	5	909	5	914	5	921	5
	1.00	912	5	912	5	916	5	921	5	928	5	933	5	938	5	946	5
	1.25	935	5	936	5	944	5	951	5	959	5	964	5	970	5	979	5
	1.50	962	5	967	5	979	5	989	5	998	5	1004	5	1011	5	1020	5
	1.75	998	5	1007	5	1024	5	1036	5	1046	5	1053	5	1060	5	1071	2
	2.00	1046	5	1058	5	1077	2	1090	2	1100	2	1108	2	1115	2	1127	2
16	0.00	867	5	874	5	885	5	892	5	899	5	903	5	908	5	915	5
	0.25	871	5	879	5	890	5	897	5	904	5	908	5	913	5	920	5
	0.50	880	5	888	5	899	5	907	5	914	5	919	5	924	5	931	5
	0.75	899	5	903	5	915	5	923	5	930	5	935	5	941	5	948	5
	1.00	921	5	925	5	937	5	946	5	954	5	959	5	965	5	973	5
	1.25	947	5	952	5	966	5	976	5	985	5	991	5	997	5	1006	5
	1.50	978	5	987	5	1004	5	1015	5	1024	5	1031	5	1038	5	1048	5
	1.75	1019	5	1031	5	1049	5	1062	5	1072	2	1079	2	1086	2	1097	2
	2.00	1069	2	1082	2	1101	2	1114	2	1125	2	1133	2	1141	2	1153	2
18	0.00	889	5	897	5	909	5	917	5	924	5	929	5	934	5	941	5
	0.25	894	5	901	5	913	5	922	5	929	5	934	5	939	5	947	5
	0.50	903	5	911	5	923	5	932	5	939	5	945	5	950	5	958	5
	0.75	918	5	926	5	940	5	949	5	957	5	962	5	968	5	976	5
	1.00	940	5	949	5	964	5	974	5	982	5	988	5	994	5	1003	5
	1.25	969	5	980	5	995	5	1006	5	1015	5	1022	5	1029	5	1039	5
	1.50	1007	5	1018	5	1036	5	1048	5	1058	5	1065	2	1072	2	1082	2
	1.75	1053	5	1065	2	1083	2	1096	2	1107	2	1114	2	1122	2	1134	2
	2.00	1104	2	1117	2	1138	2	1152	2	1164	2	1173	1	1181	1	1194	1
20	0.00	910	5	918	5	931	5	940	5	947	5	953	5	958	5	966	5
	0.25	895	5	903	5	915	5	924	5	931	5	936	5	941	5	949	5
	0.50	890	5	898	5	910	5	918	5	925	5	930	5	935	5	943	5
	0.75	904	5	907	5	913	5	922	5	929	5	934	5	939	5	947	5
	1.00	926	6	926	5	931	5	936	5	942	5	948	5	953	5	962	5
	1.25	950	6	950	6	954	5	959	5	965	5	971	5	977	5	986	5
	1.50	975	6	975	5	982	5	988	5	997	5	1003	5	1010	5	1019	5
	1.75	1001	5	1005	5	1016	5	1028	5	1038	5	1045	5	1052	5	1063	5
	2.00	1036	5	1044	5	1063	5	1076	5	1086	2	1094	2	1101	2	1113	2
25	0.00	962	5	972	5	987	5	997	5	1006	5	1012	5	1019	5	1028	2
	0.25	960	5	970	5	985	5	995	5	1004	5	1010	5	1017	5	1026	5
	0.50	966	5	976	5	991	5	1002	5	1011	5	1017	5	1024	5	1033	5
	0.75	980	5	990	5	1007	5	1018	5	1027	5	1034	5	1041	5	1051	2
	1.00	1003	5	1015	5	1032	5	1044	5	1054	2	1060	2	1067	2	1077	2
	1.25	1037	5	1049	5	1067	2	1079	2	1089	2	1096	2	1104	2	1115	2
	1.50	1078	2	1091	2	1110	2	1124	2	1135	2	1143	2	1151	2	1164	1
	1.75	1128	2	1142	2	1164	1	1179	1	1191	1	1200	1	1209	1	1222	1
	2.00	1188	1	1203	1	1227	1	1244	1	1258	1	1268	1	1278	1	1293	1
30	0.00	1010	5	1022	2	1037	2	1048	2	1058	2	1064	2	1071	2	1081	2
	0.25	1000	5	1011	5	1028	5	1039	2	1048	2	1055	2	1062	2	1071	2
	0.50	1002	5	1013	5	1030	5	1042	2	1051	2	1057	2	1064	2	1074	2
	0.75	1015	5	1026	5	1044	5	1055	2	1065	2	1072	2	1079	2	1089	2
	1.00	1039	5	1051	5	1068	2	1081	2	1091	2	1098	2	1106	2	1117	2
	1.25	1073	2	1085	2	1104	2	1118	2	1129	2	1137	2	1145	2	1157	2
	1.50	1117	2	1131	2	1152	2	1167	1	1179	1	1188	1	1197	1	1210	1
	1.75	1173	1	1188	1	1211	1	1228	1	1241	1	1251	1	1261	1	1275	1
	2.00	1239	1	1256	1	1283	1	1301	1	1316	1	1327	1	1339	1	1355	1

Table 8.6.4 CS and RTC Using The Modified Graff Strength Formula Excluding Cost of Placing and Compaction

Slump , mm

		50		60		80		100		125		150		175		200	
fck MPa	SP %	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	**515**	**5**	**521**	**5**	531	5	537	5	543	5	547	5	551	5	557	5
	0.25	523	6	523	5	**526**	**5**	**530**	**5**	**536**	**5**	540	5	544	5	550	5
	0.50	537	5	537	5	537	5	537	5	538	5	**539**	**5**	**541**	**5**	**544**	**5**
	0.75	552	5	552	5	552	5	552	5	552	5	552	5	552	5	552	5
	1.00	567	5	567	5	567	5	567	5	567	5	567	5	567	5	567	5
	1.25	582	5	582	5	582	5	582	5	582	5	582	5	582	5	582	5
	1.50	599	5	599	5	599	5	599	5	599	5	599	5	599	5	599	5
	1.75	619	5	619	5	619	5	619	5	619	5	619	5	619	5	619	5
	2.00	640	5	640	5	640	5	640	5	640	5	640	5	640	5	640	5
16	0.00	536	5	543	5	554	5	561	5	567	5	571	5	576	5	583	5
	0.25	**532**	**5**	**536**	**5**	546	5	553	5	559	5	563	5	568	5	574	5
	0.50	543	5	543	5	**545**	**5**	**548**	**5**	**552**	**5**	**556**	**5**	**560**	**5**	567	5
	0.75	558	5	558	5	558	5	558	5	558	5	559	5	561	5	**563**	**5**
	1.00	573	5	573	5	573	5	573	5	573	5	573	5	573	5	573	5
	1.25	589	5	589	5	589	5	589	5	589	5	589	5	589	5	589	5
	1.50	607	5	607	5	607	5	607	5	607	5	607	5	607	5	607	5
	1.75	626	5	626	5	626	5	626	5	626	5	626	5	626	5	626	5
	2.00	648	5	648	5	648	5	648	5	648	5	648	5	648	5	648	5
18	0.00	558	5	565	5	577	5	585	5	591	5	596	5	601	5	608	5
	0.25	**549**	**5**	557	5	568	5	575	5	582	5	587	5	591	5	598	5
	0.50	550	5	**553**	**5**	**560**	**5**	568	5	574	5	578	5	583	5	590	5
	0.75	564	5	564	5	564	5	**567**	**5**	**570**	**5**	**572**	**5**	**577**	**5**	584	5
	1.00	580	5	580	5	580	5	580	6	580	5	580	5	581	5	**585**	**5**
	1.25	596	5	596	5	596	5	596	5	596	5	596	5	596	5	596	5
	1.50	614	5	614	5	614	5	614	5	614	5	614	5	614	5	614	5
	1.75	634	5	634	5	634	5	634	5	634	5	634	5	634	5	634	5
	2.00	655	5	655	5	655	5	655	5	655	5	655	5	655	5	655	5
20	0.00	577	5	585	5	598	5	606	5	614	5	619	5	624	5	632	5
	0.25	**551**	**5**	558	5	569	5	577	5	584	5	589	5	593	5	600	5
	0.50	552	6	**552**	**6**	**555**	**5**	**558**	**5**	**562**	**5**	**566**	**5**	571	5	577	5
	0.75	568	5	568	5	568	5	568	5	568	5	568	5	**568**	**5**	**569**	**5**
	1.00	584	5	584	5	584	5	584	5	584	5	584	5	584	5	584	5
	1.25	601	5	601	5	601	5	601	5	601	5	601	5	601	5	601	5
	1.50	619	5	619	5	619	5	619	5	619	5	619	5	619	5	619	5
	1.75	638	5	638	5	638	5	638	5	638	5	638	5	638	5	638	5
	2.00	660	5	660	5	660	5	660	5	660	5	660	5	660	5	660	5
25	0.00	627	5	636	5	651	5	661	5	669	5	675	5	682	5	691	5
	0.25	610	5	618	5	632	5	642	5	650	5	656	5	662	5	671	5
	0.50	596	5	604	5	618	5	627	5	635	5	640	5	646	5	654	5
	0.75	**586**	**5**	**594**	**5**	607	5	616	5	624	5	629	5	635	5	643	5
	1.00	595	6	596	5	**603**	**5**	**610**	**5**	**618**	**5**	**623**	**5**	**629**	**5**	**637**	**5**
	1.25	612	5	612	5	612	5	616	5	620	5	**623**	**5**	**629**	**5**	**637**	**5**
	1.50	631	5	631	5	631	5	631	5	632	5	635	5	638	5	644	5
	1.75	651	5	651	5	651	5	651	5	651	5	652	5	656	5	661	5
	2.00	673	5	673	5	673	5	673	5	673	5	675	5	679	5	685	5
30	0.00	673	5	684	5	700	5	711	2	720	2	727	2	733	2	743	2
	0.25	646	5	656	5	672	5	683	5	692	5	698	5	705	5	714	5
	0.50	626	5	636	5	651	5	661	5	670	5	676	5	682	5	691	5
	0.75	613	5	622	5	637	5	646	5	655	5	661	5	667	5	676	5
	1.00	**609**	**5**	**615**	**5**	**629**	**5**	639	6	647	5	653	5	659	5	**667**	**5**
	1.25	621	6	622	5	630	5	**638**	**5**	**646**	**5**	**652**	**5**	**658**	**5**	**667**	**5**
	1.50	640	5	640	5	642	5	648	5	654	5	660	5	666	5	675	5
	1.75	660	5	660	5	660	5	666	5	672	5	676	5	683	5	692	5
	2.00	682	5	682	5	683	5	691	5	697	5	703	5	710	5	720	5

Table 8.6.5 CS and RTC Using The Modified Graff Strength Formula Including Cost of Placing and Compaction

		Slump , mm															
		50		60		80		100		125		150		175		200	
fck MPa	SP %	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	526	5	532	5	541	5	547	5	553	5	557	5	561	5	567	5
	0.25	533	6	533	5	536	5	541	5	546	5	550	5	554	5	559	5
	0.50	548	5	548	5	548	5	547	5	548	5	549	5	551	5	553	5
	0.75	562	5	562	5	562	5	562	5	562	5	562	5	562	5	562	5
	1.00	577	5	577	5	577	5	577	5	577	5	576	5	576	5	576	5
	1.25	593	5	593	5	592	5	592	5	592	5	592	5	592	5	592	5
	1.50	610	5	610	5	610	5	610	5	609	5	609	5	609	5	609	5
	1.75	629	5	629	5	629	5	629	5	629	5	629	5	629	5	629	5
	2.00	651	5	650	5	650	5	650	5	650	5	650	5	650	5	650	5
16	0.00	547	5	554	5	564	5	571	5	577	5	581	5	586	5	592	5
	0.25	542	5	546	5	556	5	563	5	569	5	573	5	578	5	584	5
	0.50	554	5	554	5	555	5	558	5	562	5	566	5	570	5	577	5
	0.75	569	5	568	5	568	5	568	5	568	5	569	5	570	5	573	5
	1.00	584	5	584	5	584	5	583	5	583	5	583	5	583	5	583	5
	1.25	600	5	600	5	600	5	599	5	599	5	599	5	599	5	599	5
	1.50	617	5	617	5	617	5	617	5	617	5	617	5	617	5	617	5
	1.75	637	5	637	5	637	5	636	5	636	5	636	5	636	5	636	5
	2.00	658	5	658	5	658	5	658	5	658	5	658	5	658	5	658	5
18	0.00	568	5	576	5	587	5	595	5	601	5	606	5	611	5	618	5
	0.25	560	5	567	5	578	5	586	5	592	5	597	5	601	5	608	5
	0.50	560	5	563	5	570	5	578	5	584	5	588	5	593	5	600	5
	0.75	575	5	575	5	574	5	577	5	580	5	582	5	587	5	594	5
	1.00	590	5	590	5	590	5	590	6	590	5	590	5	591	5	594	5
	1.25	607	5	607	5	606	5	606	5	606	5	606	5	606	5	606	5
	1.50	625	5	624	5	624	5	624	5	624	5	624	5	624	5	624	5
	1.75	644	5	644	5	644	5	644	5	644	5	644	5	644	5	644	5
	2.00	666	5	666	5	666	5	665	5	665	5	665	5	665	5	665	5
20	0.00	588	5	596	5	608	5	616	5	624	5	629	5	634	5	642	5
	0.25	561	5	569	5	580	5	587	5	594	5	598	5	603	5	610	5
	0.50	563	6	563	6	565	5	568	5	572	5	576	5	581	5	587	5
	0.75	579	5	578	5	578	5	578	5	578	5	578	5	578	5	579	5
	1.00	594	5	594	5	594	5	594	5	594	5	594	5	594	5	594	5
	1.25	611	5	611	5	611	5	611	5	611	5	611	5	610	5	610	5
	1.50	629	5	629	5	629	5	629	5	629	5	629	5	629	5	628	5
	1.75	649	5	649	5	649	5	648	5	648	5	648	5	648	5	648	5
	2.00	671	5	670	5	670	5	670	5	670	5	670	5	670	5	670	5
25	0.00	637	5	647	5	661	5	671	5	679	5	685	5	692	5	701	5
	0.25	620	5	629	5	643	5	652	5	660	5	666	5	672	5	680	5
	0.50	606	5	615	5	628	5	637	5	645	5	650	5	656	5	664	5
	0.75	597	5	605	5.	617	5	626	5	634	5	639	5	645	5	653	5
	1.00	605	6	606	5	613	5	620	5	628	5	633	5	639	5	647	5
	1.25	623	5	622	5	622	5	626	5	630	5	633	5	638	5	647	5
	1.50	641	5	641	5	641	5	641	5	642	5	645	5	648	5	654	5
	1.75	661	5	661	5	661	5	661	5	661	5	662	5	666	5	671	5
	2.00	683	5	683	5	683	5	683	5	683	5	685	5	689	5	695	5
30	0.00	684	5	694	5	711	5	721	2	730	2	737	2	743	2	753	2
	0.25	657	5	667	5	682	5	693	5	702	5	708	5	715	5	724	5
	0.50	637	5	646	5	661	5	671	5	680	5	686	5	692	5	701	5
	0.75	624	5	633	5	647	5	657	5	665	5	671	5	677	5	685	5
	1.00	620	5	625	5	639	5	649	6	657	5	663	5	669	5	677	5
	1.25	631	6	632	5	640	5	648	5	656	5	662	5	668	5	677	5
	1.50	650	5	650	5	653	5	658	5	664	5	670	5	676	5	685	5
	1.75	671	5	670	5	670	5	676	5	682	5	686	5	693	5	702	5
	2.00	693	5	693	5	693	5	701	5	707	5	713	5	720	5	730	5

Table 8.6.6 CS and RTC Using The Modified Graff Strength Formula Including Cost of Formwork and Scaffolding

Slump , mm

fck MPa	SP %	50		60		80		100		125		150		175		200	
		RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	835	5	841	5	851	5	857	5	863	5	866	5	871	5	876	5
	0.25	843	6	843	5	846	5	850	5	856	5	859	5	863	5	869	5
	0.50	858	5	858	5	857	5	857	5	858	5	859	5	860	5	863	5
	0.75	872	5	872	5	872	5	872	5	872	5	871	5	871	5	871	5
	1.00	887	5	887	5	887	5	886	5	886	5	886	5	886	5	886	5
	1.25	903	5	902	5	902	5	902	5	902	5	902	5	902	5	902	5
	1.50	920	5	920	5	919	5	919	5	919	5	919	5	919	5	919	5
	1.75	939	5	939	5	939	5	939	5	938	5	938	5	938	5	938	5
	2.00	960	5	960	5	960	2	960	5	960	5	960	5	960	5	960	5
16	0.00	857	5	863	5	874	5	881	5	887	5	891	5	896	5	902	5
	0.25	852	5	856	5	866	5	873	5	879	5	883	5	887	5	894	5
	0.50	864	5	863	5	865	5	868	5	872	5	876	5	880	5	886	5
	0.75	878	5	878	5	878	5	878	5	878	5	878	5	880	5	883	5
	1.00	894	5	893	5	893	5	893	5	893	5	893	5	893	5	893	5
	1.25	910	5	910	5	909	5	909	5	909	5	903	5	909	5	909	5
	1.50	927	5	927	5	927	5	927	5	927	5	927	5	927	5	927	5
	1.75	947	5	946	5	946	5	946	5	946	5	946	5	946	5	946	5
	2.00	968	5	968	5	968	5	968	5	968	5	967	5	967	5	967	5
18	0.00	878	5	885	5	897	5	904	5	911	5	916	5	920	5	928	5
	0.25	870	5	877	5	888	5	895	5	902	5	906	5	911	5	918	5
	0.50	870	5	873	5	880	5	887	5	894	5	898	5	903	5	910	5
	0.75	885	5	884	5	884	5	887	5	890	5	892	5	897	5	903	5
	1.00	900	5	900	5	900	5	900	5	900	5	900	5	901	5	904	5
	1.25	917	5	916	5	916	5	916	5	916	5	916	5	916	5	916	5
	1.50	934	5	934	5	934	5	934	5	934	5	934	5	934	5	934	5
	1.75	954	5	954	5	954	5	954	5	953	5	953	5	953	5	953	5
	2.00	976	5	975	5	975	5	975	5	975	5	975	5	975	5	975	5
20	0.00	898	5	906	5	918	5	926	5	933	5	938	5	944	5	951	5
	0.25	871	5	878	5	889	5	897	5	904	5	908	5	913	5	920	5
	0.50	873	6	872	6	875	5	878	5	882	5	886	5	891	5	897	5
	0.75	888	5	888	5	888	5	888	5	888	5	888	5	888	5	889	5
	1.00	904	5	904	5	904	5	904	5	904	5	904	5	904	5	904	5
	1.25	921	5	921	5	921	5	920	5	920	5	920	5	920	5	920	5
	1.50	939	5	939	5	939	5	938	5	938	5	938	5	938	5	938	5
	1.75	959	5	959	5	958	5	958	5	958	5	958	5	958	5	958	5
	2.00	980	5	980	5	980	5	980	5	980	5	980	5	980	5	980	5
25	0.00	947	5	956	5	971	5	981	5	989	5	995	5	1001	5	1010	5
	0.25	930	5	939	5	952	5	962	5	970	5	976	5	982	5	990	5
	0.50	916	5	924	5	938	5	947	5	954	5	960	5	966	5	974	5
	0.75	906	5	914	5	927	5	936	5	943	5	949	5	954	5	962	5
	1.00	915	6	916	5	923	5	930	5	938	5	943	5	948	5	956	5
	1.25	932	5	932	5	932	5	936	5	940	5	943	5	948	5	956	5
	1.50	951	5	951	5	951	5	950	5	952	5	955	5	958	5	963	5
	1.75	971	5	971	5	971	5	971	5	970	5	972	5	975	5	981	5
	2.00	993	5	993	5	993	5	992	5	992	5	994	5	998	5	1004	5
30	0.00	993	5	1004	5	1020	5	1031	2	1040	2	1046	2	1053	2	1062	2
	0.25	966	5	976	5	992	5	1002	5	1011	5	1018	5	1024	5	1034	5
	0.50	947	5	956	5	971	5	981	5	989	5	995	5	1002	5	1011	5
	0.75	933	5	942	5	956	5	966	5	974	5	980	5	986	5	995	5
	1.00	930	5	935	5	949	5	959	5	967	5	972	5	978	5	987	5
	1.25	941	6	942	5	950	5	958	5	966	5	972	5	978	5	987	5
	1.50	960	5	960	5	962	5	968	5	974	5	980	5	986	5	995	5
	1.75	980	5	980	5	980	5	986	5	991	5	996	5	1003	5	1012	5
	2.00	1002	5	1002	5	1003	5	1010	5	1016	5	1022	5	1029	5	1039	5

Table 8.6.7 CS and RTC Using The Feret Strength Formula Excluding Cost of Placing and Compaction

Slump , mm

fck MPa	SP %	50		60		80		100		125		150		175		200	
		RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	**498**	**5**	**498**	**5**	**500**	**5**	**503**	**5**	**508**	**5**	**511**	**5**	**515**	**5**	**520**	**5**
	0.25	514	5	514	5	514	5	514	5	515	5	516	5	517	5	**520**	**5**
	0.50	531	5	531	5	531	5	531	5	531	5	531	5	531	5	531	5
	0.75	548	5	548	5	548	5	548	5	548	5	548	5	548	5	548	5
	1.00	565	5	565	5	565	5	565	5	565	5	565	5	565	5	565	5
	1.25	583	5	583	5	583	5	583	5	583	5	583	5	583	5	583	5
	1.50	601	5	601	5	601	5	601	5	601	5	601	5	601	5	601	5
	1.75	620	5	620	5	620	5	620	5	620	5	620	5	620	5	620	5
	2.00	639	5	639	5	639	5	639	5	639	5	639	5	639	5	639	5
16	0.00	**514**	**5**	**521**	**5**	530	5	537	5	542	5	546	5	550	5	556	5
	0.25	524	5	525	5	**529**	**5**	**536**	**5**	**541**	**5**	**545**	**5**	**549**	**5**	**555**	**5**
	0.50	541	5	541	5	541	5	542	5	545	5	546	5	551	5	557	5
	0.75	558	5	558	5	558	5	558	5	558	5	558	5	560	5	563	5
	1.00	576	5	576	5	576	5	576	5	576	5	576	5	576	5	576	5
	1.25	594	5	594	5	594	5	594	5	594	5	594	5	594	5	594	5
	1.50	612	5	612	5	612	5	612	5	612	5	612	5	612	5	612	5
	1.75	632	5	632	5	632	5	632	5	632	5	632	5	632	5	632	5
	2.00	651	5	652	5	651	5	651	5	651	5	651	5	651	5	651	5
18	0.00	547	5	554	5	564	2	571	2	576	2	580	2	584	2	590	2
	0.25	**545**	**5**	**552**	**5**	**563**	**5**	**569**	**2**	**575**	**2**	**579**	**2**	**583**	**2**	**589**	**2**
	0.50	551	5	554	5	**563**	**5**	571	5	577	5	580	2	585	2	591	2
	0.75	567	5	567	5	571	5	574	5	580	5	585	5	589	5	596	2
	1.00	586	5	586	5	586	5	586	5	590	5	592	5	595	5	602	5
	1.25	604	5	604	5	604	5	604	5	604	5	605	5	608	5	612	5
	1.50	623	5	623	5	623	5	623	5	623	5	623	5	623	5	627	5
	1.75	643	5	643	5	643	5	643	5	643	5	643	5	643	5	643	5
	2.00	663	5	663	5	663	5	663	5	663	5	663	5	663	5	663	5
20	0.00	577	2	584	2	595	2	602	2	608	2	613	2	618	2	624	1
	0.25	559	5	566	2	576	2	583	2	589	2	593	2	597	2	604	2
	0.50	**556**	**5**	**559**	**5**	**564**	**5**	**571**	**5**	578	5	582	3	585	2	591	2
	0.75	574	5	574	5	574	5	574	5	**576**	**5**	**579**	**5**	**581**	**5**	**586**	**5**
	1.00	593	5	593	5	593	5	593	5	593	5	593	5	593	5	593	5
	1.25	611	5	611	5	611	5	611	5	611	5	611	5	611	5	611	5
	1.50	631	5	631	5	631	5	631	5	631	5	631	5	631	5	631	5
	1.75	651	5	651	5	651	5	651	5	651	5	651	5	651	5	651	5
	2.00	671	5	671	5	671	5	671	5	671	5	671	5	671	5	671	5
25	0.00	655	1	664	1	678	1	688	1	696	1	701	1	707	1	716	1
	0.25	644	1	653	1	666	1	676	1	683	1	689	1	695	1	703	1
	0.50	639	1	647	1	661	1	670	1	678	1	683	1	689	1	697	1
	0.75	**637**	**1**	**646**	**1**	**659**	**1**	**669**	**1**	**677**	**1**	**682**	**1**	**688**	**1**	**696**	**1**
	1.00	641	2	649	2	662	1	672	1	680	1	685	1	691	1	700	1
	1.25	653	2	659	2	670	2	678	1	686	1	692	1	698	1	707	1
	1.50	667	4	673	2	681	2	690	1	697	1	703	1	709	1	718	1
	1.75	682	5	689	3	698	2	705	2	712	1	717	1	723	1	732	1
	2.00	702	5	708	3	716	2	724	2	731	1	735	1	741	1	751	1
30	0.00	743	1	755	1	773	1	785	1	795	1	805	1	815	1	831	1
	0.25	718	1	729	1	745	1	757	1	767	1	774	1	781	1	792	1
	0.50	704	1	714	1	731	1	742	1	751	1	758	1	765	1	775	1
	0.75	**698**	**1**	**708**	**1**	**725**	**1**	**736**	**1**	**745**	**1**	**752**	**1**	**759**	**1**	**769**	**1**
	1.00	**698**	**1**	709	1	**725**	**1**	**736**	**1**	746	1	753	1	760	1	770	1
	1.25	704	1	715	1	731	1	743	1	752	1	759	1	767	1	777	1
	1.50	714	1	725	1	742	1	754	1	764	1	771	1	779	1	789	1
	1.75	730	1	741	1	758	1	771	1	781	1	789	1	796	1	807	1
	2.00	750	1	760	1	779	1	792	1	803	1	811	1	819	1	831	1

Table 8.6.8 CS and RTC Using The Feret Strength Formula Including Cost of Placing and Compaction .

fck MPa	SP %	Slump , mm 50		60		80		100		125		150		175		200	
		RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	**509**	**5**	**508**	**5**	**510**	**5**	**513**	**5**	**518**	**5**	**521**	**5**	**525**	**5**	**530**	**5**
	0.25	525	5	525	5	524	5	524	5	525	5	526	5	527	5	**530**	**5**
	0.50	541	5	541	5	541	5	541	5	541	5	541	5	541	5	541	5
	0.75	558	5	558	5	558	5	558	5	558	5	557	5	557	5	557	5
	1.00	575	5	575	5	575	5	575	5	575	5	575	5	575	5	575	5
	1.25	593	5	593	5	593	5	593	5	593	5	593	5	592	5	592	5
	1.50	611	5	611	5	611	5	611	5	611	5	611	5	611	5	611	5
	1.75	630	5	630	5	630	5	630	5	630	5	630	5	630	5	630	5
	2.00	650	5	650	5	649	5	649	5	649	5	649	5	649	5	649	5
16	0.00	**525**	**5**	**531**	**5**	540	5	547	5	552	5	556	5	560	5	566	5
	0.25	534	5	536	5	**539**	**5**	**546**	**5**	**551**	**5**	**555**	**5**	**559**	**5**	**565**	**5**
	0.50	551	5	551	5	551	5	553	5	555	5	556	5	561	5	567	5
	0.75	568	5	568	5	568	5	568	5	568	5	568	5	570	5	573	5
	1.00	586	5	586	5	586	5	586	5	586	5	585	5	585	5	583	5
	1.25	604	5	604	5	604	5	604	5	604	5	604	5	604	5	604	5
	1.50	623	5	623	5	623	5	622	5	622	5	622	5	622	5	622	5
	1.75	642	5	642	5	642	5	642	5	641	5	641	5	641	5	641	5
	2.00	662	5	662	5	662	5	661	5	661	5	661	5	661	5	661	5
18	0.00	558	5	565	5	574	2	581	2	586	2	590	2	594	2	600	2
	0.25	**555**	**5**	**562**	**5**	**573**	**5**	**580**	**2**	**585**	**2**	**589**	**2**	**593**	**2**	**599**	**2**
	0.50	562	5	565	5	**573**	**5**	581	5	587	5	590	2	594	2	600	2
	0.75	578	5	578	5	581	5	584	5	590	5	595	5	599	5	605	2
	1.00	596	5	596	5	596	5	596	5	600	5	602	5	605	5	612	5
	1.25	615	5	614	5	614	5	614	5	614	5	615	5	618	5	622	5
	1.50	634	5	633	5	633	5	633	5	633	5	633	5	633	5	637	5
	1.75	653	5	653	5	653	5	653	5	653	5	653	5	652	5	653	5
	2.00	673	5	673	5	673	5	673	5	673	5	673	5	673	5	673	5
20	0.00	587	2	594	2	605	2	612	2	618	2	623	2	628	2	634	1
	0.25	569	5	577	2	586	2	593	2	599	2	603	2	607	2	614	2
	0.50	**567**	**5**	**569**	**5**	**574**	**5**	**582**	**5**	588	5	592	3	595	2	601	2
	0.75	585	5	585	5	585	5	584	5	**586**	**5**	**588**	**5**	**591**	**5**	**596**	**5**
	1.00	603	5	603	5	603	5	603	5	603	5	603	5	603	5	603	5
	1.25	622	5	622	5	622	5	622	5	621	5	621	5	621	5	621	5
	1.50	641	5	641	5	641	5	641	5	641	5	641	5	641	5	641	5
	1.75	661	5	661	5	661	5	661	5	661	5	660	5	660	5	660	5
	2.00	681	5	681	5	681	5	681	5	681	5	681	5	681	5	681	5
25	0.00	666	1	674	1	688	1	698	1	706	1	711	1	717	1	726	1
	0.25	655	1	663	1	676	1	686	1	693	1	699	1	705	1	713	1
	0.50	649	1	658	1	671	1	680	1	688	1	693	1	699	1	707	1
	0.75	**648**	**1**	**656**	**1**	**670**	**1**	**679**	**1**	**687**	**1**	**692**	**1**	**698**	**1**	**706**	**1**
	1.00	652	2	660	2	672	1	682	1	690	1	695	1	701	1	709	1
	1.25	664	2	669	2	680	2	688	1	696	1	702	1	708	1	717	1
	1.50	678	4	683	2	692	2	700	1	707	1	712	1	719	1	728	1
	1.75	693	5	700	3	708	2	715	2	722	1	727	1	733	1	742	1
	2.00	712	5	718	3	727	2	734	2	741	1	745	1	751	1	761	1
30	0.00	754	1	765	1	783	1	795	1	805	1	815	1	825	1	841	1
	0.25	728	1	739	1	756	1	767	1	777	1	784	1	791	1	802	1
	0.50	714	1	725	1	741	1	752	1	761	1	768	1	775	1	785	1
	0.75	**709**	**1**	**719**	**1**	**735**	**1**	**746**	**1**	**755**	**1**	**762**	**1**	**769**	**1**	**779**	**1**
	1.00	**709**	**1**	**719**	**1**	**735**	**1**	747	1	756	1	763	1	770	1	780	1
	1.25	715	1	725	1	742	1	753	1	762	1	769	1	776	1	787	1
	1.50	725	1	736	1	753	1	764	1	774	1	781	1	789	1	799	1
	1.75	740	1	751	1	769	1	781	1	791	1	799	1	806	1	817	1
	2.00	761	1	771	1	789	1	802	1	813	1	821	1	829	1	841	1

Table 8.6.9 *CS and RTC Using The Feret Strength Formula Including Cost of Formwork and Scaffolding*

fck MPa	SP %	Slump, mm 50		60		80		100		125		150		175		200	
		RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS	RTC	CS
14	0.00	**818**	**5**	**818**	**5**	**820**	**5**	**823**	**5**	**828**	**5**	**831**	**5**	**834**	**5**	**839**	**5**
	0.25	834	5	834	5	834	5	834	5	835	5	836	5	837	5	840	5
	0.50	851	5	851	5	851	5	851	5	850	5	850	5	850	5	850	5
	0.75	868	5	868	5	868	5	867	5	867	5	867	5	867	5	867	5
	1.00	885	5	885	5	885	5	885	5	885	5	885	5	884	5	884	5
	1.25	903	5	903	5	903	5	902	5	902	5	902	5	902	5	902	5
	1.50	921	5	921	5	921	5	921	5	921	5	921	5	920	5	920	5
	1.75	940	5	940	5	940	5	940	5	939	5	939	5	939	5	939	5
	2.00	959	5	959	5	959	5	959	5	959	5	959	5	959	5	959	5
16	0.00	**835**	**5**	**841**	**5**	850	5	857	5	862	5	866	5	870	5	876	5
	0.25	844	5	845	5	**849**	**5**	**855**	**5**	**861**	**5**	**865**	**5**	**869**	**5**	**875**	**5**
	0.50	861	5	861	5	860	5	862	5	864	5	866	5	870	5	876	5
	0.75	878	5	878	5	878	5	878	5	878	5	878	5	880	5	882	5
	1.00	896	5	896	5	896	5	895	5	895	5	895	5	895	5	895	5
	1.25	914	5	914	5	914	5	914	5	913	5	913	5	913	5	913	5
	1.50	933	5	932	5	932	5	932	5	932	5	932	5	932	5	932	5
	1.75	852	5	952	5	951	5	951	5	951	2	951	5	951	5	951	5
	2.00	972	5	972	5	971	5	971	5	971	5	971	5	971	5	971	5
18	0.00	867	5	874	5	884	2	891	2	896	2	900	2	904	2	910	2
	0.25	**865**	**5**	**872**	**5**	**883**	**5**	**889**	**2**	**895**	**2**	**899**	**2**	**903**	**2**	**909**	**2**
	0.50	872	5	874	5	**883**	**5**	890	5	897	5	900	2	904	2	910	2
	0.75	888	5	888	5	891	5	894	5	900	5	904	5	909	5	915	2
	1.00	906	5	906	5	906	5	906	5	909	5	912	5	915	5	922	5
	1.25	924	5	924	5	924	5	924	5	924	5	925	5	928	5	932	5
	1.50	943	5	943	5	943	5	943	5	943	5	943	5	943	5	946	5
	1.75	963	5	963	5	963	5	962	5	962	5	962	5	962	5	962	5
	2.00	983	5	983	5	983	5	983	5	983	5	982	5	982	5	982	5
20	0.00	897	2	904	2	915	2	922	2	928	2	933	2	937	2	944	1
	0.25	879	5	887	2	896	2	903	2	908	2	913	2	917	2	923	2
	0.50	**877**	**5**	**879**	**5**	**884**	**5**	**891**	**5**	898	5	902	3	905	2	911	2
	0.75	895	5	894	5	894	5	894	5	**896**	**5**	**898**	**5**	**900**	**5**	**905**	**5**
	1.00	913	5	913	5	913	5	913	5	912	5	912	5	912	5	912	5
	1.25	932	5	932	5	931	5	931	5	931	5	931	5	931	5	931	5
	1.50	951	5	951	5	951	5	951	5	950	5	950	5	950	5	950	5
	1.75	971	5	971	5	971	5	970	5	970	5	970	5	970	5	970	5
	2.00	991	5	991	5	991	5	991	5	991	5	991	5	991	5	991	5
25	0.00	975	1	984	1	998	1	1007	1	1015	1	1021	1	1027	1	1036	1
	0.25	964	1	973	1	986	1	995	1	1003	1	1009	1	1015	1	1023	1
	0.50	959	1	967	1	980	1	990	1	997	1	1003	1	1009	1	1017	1
	0.75	**958**	**1**	**966**	**1**	**979**	**1**	**989**	**1**	**996**	**1**	**1002**	**1**	**1008**	**1**	**1016**	**1**
	1.00	962	2	969	2	982	1	992	1	999	1	1005	1	1011	1	1019	1
	1.25	974	2	979	2	990	2	998	1	1006	1	1012	1	1018	1	1026	1
	1.50	987	4	993	2	1001	2	1010	1	1016	1	1022	1	1028	1	1037	1
	1.75	1003	5	1009	3	1018	2	1024	2	1031	1	1036	1	1043	1	1052	1
	2.00	1022	4	1028	3	1036	2	1044	2	1051	1	1055	1	1061	1	1071	1
30	0.00	1064	1	1075	1	1093	1	1105	1	1115	1	1125	1	1135	1	1150	1
	0.25	1038	1	1049	1	1065	1	1077	1	1087	1	1094	1	1101	1	1111	1
	0.50	1024	1	1034	1	1051	1	1062	1	1071	1	1078	1	1085	1	1095	1
	0.75	**1018**	**1**	**1029**	**1**	**1045**	**1**	**1056**	**1**	**1065**	**1**	**1072**	**1**	**1078**	**1**	**1088**	**1**
	1.00	1019	1	**1029**	**1**	**1045**	**1**	**1056**	**1**	1066	1	**1072**	**1**	1079	1	1089	1
	1.25	1024	1	1035	1	1051	1	1063	1	1072	1	1079	1	1086	1	1096	1
	1.50	1035	1	1045	1	1062	1	1074	1	1084	1	1091	1	1098	1	1109	1
	1.75	1050	1	1061	1	1078	1	1091	1	1101	1	1108	1	1116	1	1127	1
	2.00	1070	1	1081	1	1099	1	1112	1	1123	1	1131	1	1139	1	1151	1

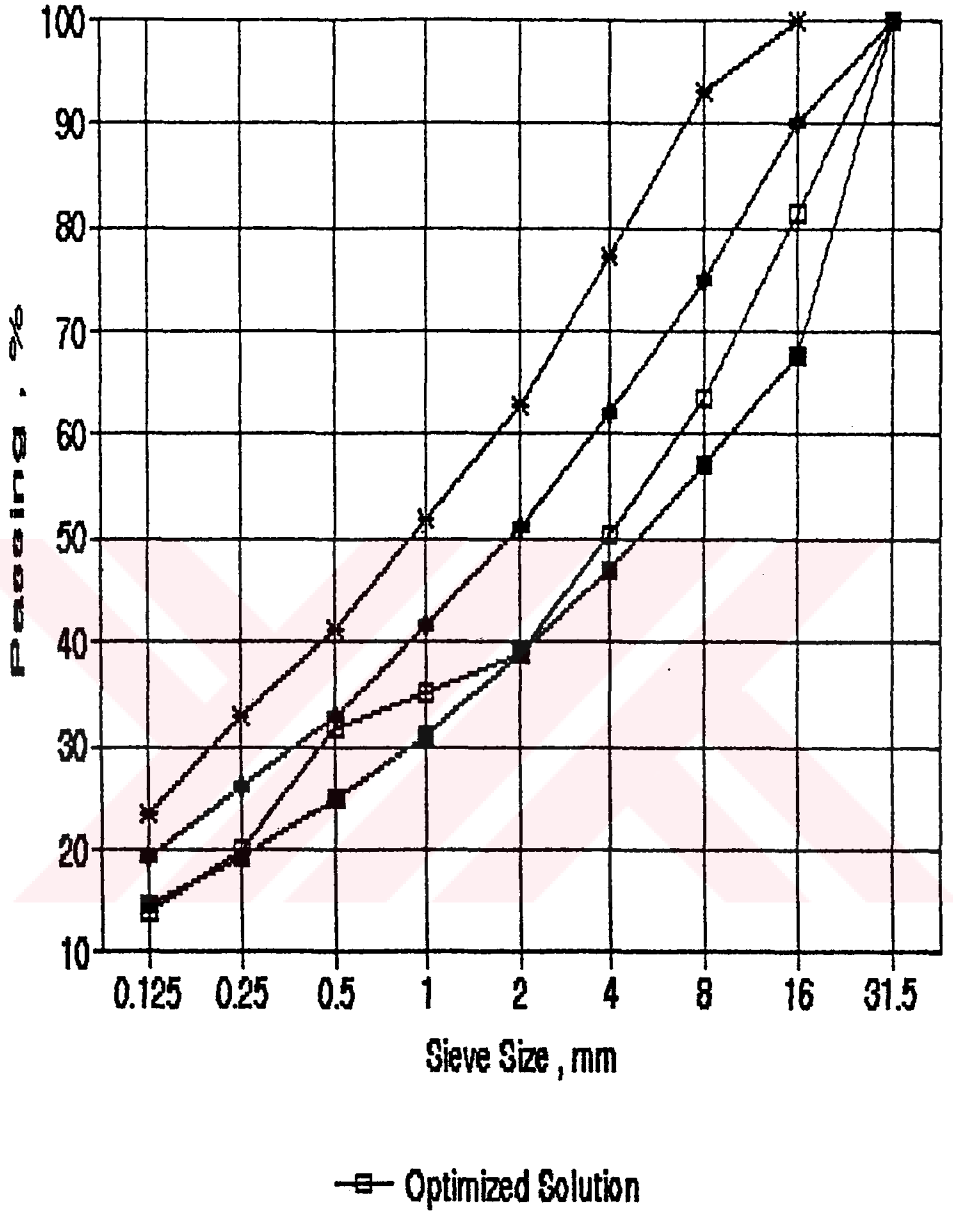


Fig. 8.3 Faury Grading Curve of C14 according to Feret formula with C=318, A1=756, A2=554, A3=582, Rsp=0

The results in Tables 8.6.1 through 8.6.9 indicate, in general, that the costs increase with increasing slump and characteristic strength.

When Graff strength formula is used (Tables 8.6.1, 8.6.2 and 8.6.3) the optimum superplasticizer dosage is zero up to C18, it rises up to 0.50% for C20, but falls down to 0.25% for C25 with only an insignificant difference of 2 kgC/m^3 concrete in cost, which means 0.00% superplasticizer dosage may also be considered as an optimum solution. The optimum dosage is 0.25% - 0.50% for C30; in this case the increase in cost being 2 kgC/m^3 conc. when admixture content is raised to 0.50%. However, the optimum superplasticizer (SP) dosage is not sensitive to workability; within a given concrete class, the optimum SP dosage does not vary with slump.

The use of Modified Graff and Feret formulae as the relations between mix parameters and strength yield optimum solutions with optimum SP dosages increasing from 0.00% up to 1.25% with concrete class and slump. The increased in SP within a given concrete class is 0.25 in the formulation with Modified Graff and 0.50% with Feret formula up to C20, and does not exceed 0.25% for C30. The optimum SP dosage determined using the Feret formula does not vary with slump.

The cost of compaction and formwork did not influence the optimum SP contents.

When Feret formula is used the control standards of optimum solutions increase from "poor" to "excellent" as the concrete class increases from C14 to C30 (Tables 8.6.7, 8.6.8 and 8.6.9). However, when Graff or Modified Graff formula is used, the control standards associated with optimum solutions is "poor" for all classes, except for C30 with 200 mm slump with the Graff formula (Table 8.6.1).

In general control standards (1 ≡ excellent, 2 ≡ very good, 3 ≡ good, 4 ≡ fair, 5 ≡ poor and 6 ≡ very poor) increase from "poor" to "excellent" with increasing SP dosage and slump. However, the results obtained with Modified Graff formula (Tables 8.6.4) give a control standard of "poor" for all solutions except for C30 with zero SP dosage and 100 to 200 mm slump. This is probably due to the significant difference in the cost of quality control for "poor" and "very poor" control standards and those starting with "good" up to "excellent" which include the cost of a laboratory in the central plants, as can be seen in Table 8.6.4.

9. DISCUSSION AND CONCLUSIONS

9.1 DISCUSSION OF RESULTS RELATED TO FRESH CONCRETE

For pumpable concrete mix design the Faury's method with some modifications and refinement provides an efficient approach to the determination of concrete mix proportions. The method includes the wall-effect as represented by the ratio of equivalent form radius to maximum particle size of concrete and the grading of solids in concrete as a whole, especially in the fraction passing 0.50 mm.

The fines content of concrete taken as the sum of absolute volume of solids passing the 200 μm sieve should be kept about 0.13 to obtain cohesive pumpable mixes. The adequacy of the cohesion of mix can be judged from the slump test observations. Slumps as a cohesive mass without shear or collapse can be taken as an indication of pumpable cohesive concretes. This was validated also by in-situ observations.

The superplasticizer (SP) in this work had air-entraining and set retarding effects. The limiting dosages 0.5 to 0.8% (Table A.3) recommended by the manufacturer are well below the dosages recommended for other commercially available superplasticizers though yielding 10 - 22 % reduction in water requirement. At 5% SP dosage, the reduction in mixing water requirement varied between 21% and 37%. However, for the practically feasible dosage of 1.25% as determined in this work (Section 8.15), the reduction in water requirement varied between 14% and 28%. It appears that for the cement used in the present work, limits of 0.7% to 1.2% could be recommended. In view of its overall performance, considering also its set-retarding and air-entraining effects and also comparable price, the admixture may be classified as a "limited superplasticizer".

Air content determined by the gravimetric and pressure methods increased from about 1% to 10% as superplasticizer dosage increased from 0% to 5%. This may be partly due to the surface active properties of the superplasticizer which reduces the surface tension. For the SP dosage of 1.25%, the entrained air contents were 3.1 - 3.6%, which are just above the maximum limit of 3% air content for normal concrete. However, for the dosages 0.5 - 0.8% recommended by the manufacturer the air entrainment is about 2 to 2.5%. The additional reduction in strength of 8% estimated using Fig. 3.1 due to the 2.5% extra air entrained is well compensated by an increase in strength of 20% due to the addition of superplasticizer estimated using Eq. 7.14 for 1.25% SP. In other words, the air entrained within the range of recommended dosages, the entrained air does not cause any reduction in strength.

In general, a deviation of temperature from 20°C results in a reduction in slump. The reduction in slump is more significant for 30°C and at higher superplasticizer dosages (Table 7.2).

The control slump (70 ± 10 mm at 20°C) reduces to 5 ± 5 mm at 30°C and 30 ± 10 mm at 12°C. The slumps at 30°C are about 0 mm and at 12°C about 25 mm for higher superplasticizer dosages. This should be taken into account when translating the 20°C laboratory results to site conditions.

9.2 DISCUSSION OF RESULTS RELATED TO HARDENED CONCRETE

It is apparent from the K_{GM} and K_F values in Table 7.5 that the use of superplasticizer resulted in an increase of 60% in $1/K_{GM}$ and 20% in K_F for an increase in SP dosage from 0.0% to 2.0%. However, there is an increase of only 8% in the value of $1/K_G$ up to 0.5% SP dosage. The relation between the relative strength and the superplasticizer content, as represented by

$$[\ f/(C/W)^2\ ]/f_{cc} = 1/K_G$$

$$[\ f/(C/(W+d_w\ V_{air}))^2\ ]/f_{cc} = 1/K_{GM} \text{ and}$$

$$f/(c/(c+a+Vair))^2 = K_F$$

given by Equations 7.12, 7.13 and 7.14 increase with increasing superplasticizer dosage of up to about 0.6%, 1.6% and 1.7%, respectively.

It is known that the rebound numbers give only a comparative result in the absence of a calibration based on experimental results. Errors of up to ± 30% are very likely if the strength is estimated from the chart provided by the manufacturer of the hammer. Based on the experimental data obtained in this work (Section 7.1) Eqs. 7.24 and 7.25 were established. Statistical analysis results show that, within the scope of this work, power function form yields a better fit for the $f_{cyl}-N_{cyl}$ data.

Linear, power and polynomial function forms to represent the relation of ultrasonic pulse velocity with compressive strength were investigated. Among these relations, Eq. 7.26, which is a power function, has the highest coefficient of correlation (r=89%).

The rebound number and ultrasonic pulse velocity, are used in combination to reduce the error in the estimation of in-situ concrete strength. Eq. 7.30 through 7.39 are obtained from statistical analyses of cylinder and cube test results. It may be concluded that, Eq. 7.32 (exponential function) gives the best fit. Nevertheless, the other relations have statistical fit characteristics not significantly below those of Eq. 7.32 (r=98.9%). This is due to the increased accuracy by the use of rebound number and pulse velocity results in combination.

yielding a relation of higher coefficient of correlation with still 2 independent coefficients as in Eq. 7.26 and 7.25.

9.3 DISCUSSION OF OPTIMUM MIX PROPORTIONS - OPTIMUM SUPERPLASTICIZER DOSAGE

The results in Tables 8.6.1 through 8.6.9 indicate, in general, that the costs increase with increasing slump and characteristic strength.

The cost of compaction and formwork did not influence the optimum compositions. The strength formula adopted in the optimisation model influences the optimum compositions and control standards. The results obtained with the Modified Graff and Feret formulae are not significantly different. However, the formulation with the Feret formula given in Tables 8.6.7, 8.6.8 and 8.6.9 can be said to be more accurate since the coefficient of correlation of the Feret formula given by Eq. 7.14 is 0.76 which is significantly higher than that of the other two with correlation coefficients of 0.64 and 0.65.

The control standards of optimum solutions increase from "poor" to "excellent" with increasing concrete class from C14 to C25. "Very poor" control standard is not encountered in optimum solutions. Optimum compositions for C14 are those with zero superplasticizer content. Therefore, for C14 the use of superplasticizer is not recommended. However, SP dosages of up to 1.25% can be recommended as the concrete class increases to C20 and above. It is also interesting to note that "poor" control standard is associated with all optimum solutions for C14 through C20 except for C18 with slumps 100mm to 200mm. "Excellent" level of control standard is associated with optimum solutions for C25 and C30 concrete classes.

The change in relative cost should be taken into consideration if, for some reason or other, the control standard is to be reduced or increased to levels other than those corresponding to minimum costs.

9.4. SUGGESTIONS FOR FUTURE WORKS

1) The optimum dosages of other types of superplasticizer or different admixture types may be investigated with different cement types.

2) Different types of formwork (steel, plastic, etc.) may be investigated and added into the optimization model.

3) The applicability of the optimum mix proportions obtained in this work may be investigated in ready-mixed concrete plants. The optimisation model can be improved and further developed.

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APPENDIX A

A.1. PROPERTIES OF CONCRETE CONSTITUENTS

Table A.1 Engineering Properties of the Concrete Constituents

Material	Cement	Aggregates No0	 No1	 No2	 No3	Water	Admixture
Type	BC32.5	Fine	Fine	Med.	Coar.	Potable	SP
Hardness	---	--	--	--	--	24 °Fr	--
Density	3.045 2.996	2.715	2.681	2.745	2.722	0.9994	1.198

Grading Sieve Size, mm	Cement	Aggregates No0	 No1	 No2	 No3	Concrete Low	 Up
31.5	100	100	100	100	100	100	100
16.0	100	100	100	100	21	77	81
8.0	100	100	100	43	0.6	63	68
4.0	100	100	90	2.8	0.5	53	59
2.0	100	100	64	1.4	0.4	43	46
1.0	100	97	55	1.2	0.4	35	39
0.5	100	93	47	1.0	0.2	27	32
0.25	100	58	19	0.4	0.1	21	26
0.2	99.9	--	--	--	--	--	--
0.125	--	9.8	5	0.1	0.05	15	20
0.09	97.6	--	--	--	--	--	--
0.075	92.3	--	--	--	--	--	--
0.063	76.9	1.3	--	--	--	--	--

Note: The grading curves are given in ***Fig. A.1***

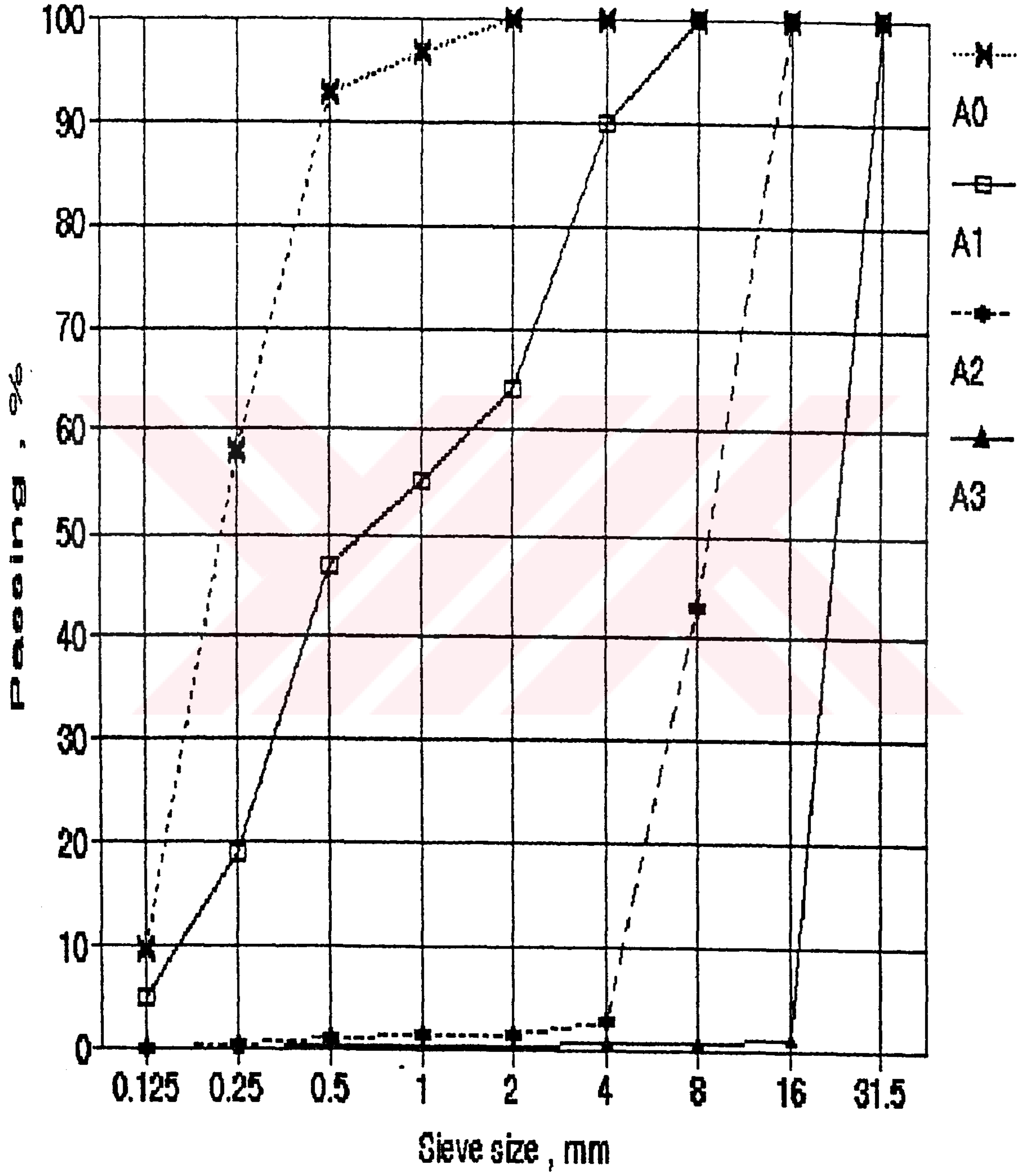


Fig. A.1 Aggregate Grading Curves (Passing Values are Given in Table A.1)

Table A.2 Chemical, Physical Properties of Blended P. Cement

(a) Chemical Composition, by weight%

Oxide Compound	Blended Cement 32.5
SiO_2	14.61
Insoluble Residue	10.16
Al_2O_3	7.90
Fe_2O_3	6.30
CaO	52.98
MgO	2.82
SO_3	2.70
Loss on Ignition	1.47
Na_2O	0.35
K_2O	0.55
TOTAL	99.84
Free Lime	1.91
$CaCO_3$	-

(b) Physical and Chemical Properties

Density Mg/m^3		
	in Paraffin	2.996
	Water	3.045
Specific Surface		
	Blaine, m^2/kg	330.1
Fineness, Retained on mesh %		
	90 µm	2.4
	200 µm	0.1
Soundness, LeChatelier mm		2
Strength, MPa		
Compressive	28 days	37.2
Flexural	28 days	6.85

Water Requirement for Standard Consistency, wt%

Rsp	0.0%	0.5%	1.0%	1.5%	2.0%	5.0%
	29.5	28.5	27.7	26.8	27.0	27.0

Setting Times, hr-min
I:Initial F:Final

Rsp	0.0%	0.5%	1.0%	1.5%	2.0%	5.0%
	1-50 I	1-50 I	1-50 I	1-55 I	2-15 I	2-15 I
	2-40 F	3-25 F	4-20 F	4-35 F	4-30 F	5-00 F

Table A.3 Prices (excluding VAT) of Some Water Reducing Agents (Supplied in 35 kg plastic Containers, August 1995).

WRA	Cost, TL/kg	Type	Recommended Dosage, wt%
Sikament	56.000	HRWR	0.8 - 3.0
Sikament-FF		HRWR	0.6 - 3.0
Sikament-FF-N	67.000	HRWR Acc.	0.8 - 3.0
Sikament-520	56.000	HRWR Ret.	0.8 - 2.5
Plastiment-BV40	37.000	WR	0.2 - 0.5
Plastiment-AR340	25.000	WR Ret. (AE)	0.2 - 0.8
Betek Flu-108	68.000	HRWR (Ret) (AE)	0.5 - 0.8

HRWR : High-Range Water-Reducing
WR : Water Reducing
Acc : Accelerating
Ret : Retarding (Ret): at dosage higher than recommended
AE : Air-Entraining (AE): at dosages higher than recommended

A.2. THE MECHANISM OF ACTION OF SUPERPLASTICIZERS

The mechanism of action of superplasticizers may be summarized as follows: The superplasticizers' action being the dispersion of cement agglomerates normally found when cement is suspended in water, these admixtures are thought to be adsorbed on the surface of cement and of other very fine particles, causing them to become matually repulsive as a result of the anionic nature of superplasticizers, which causes the cement particles to become negatively charged, as shown in *Fig. A.3.*

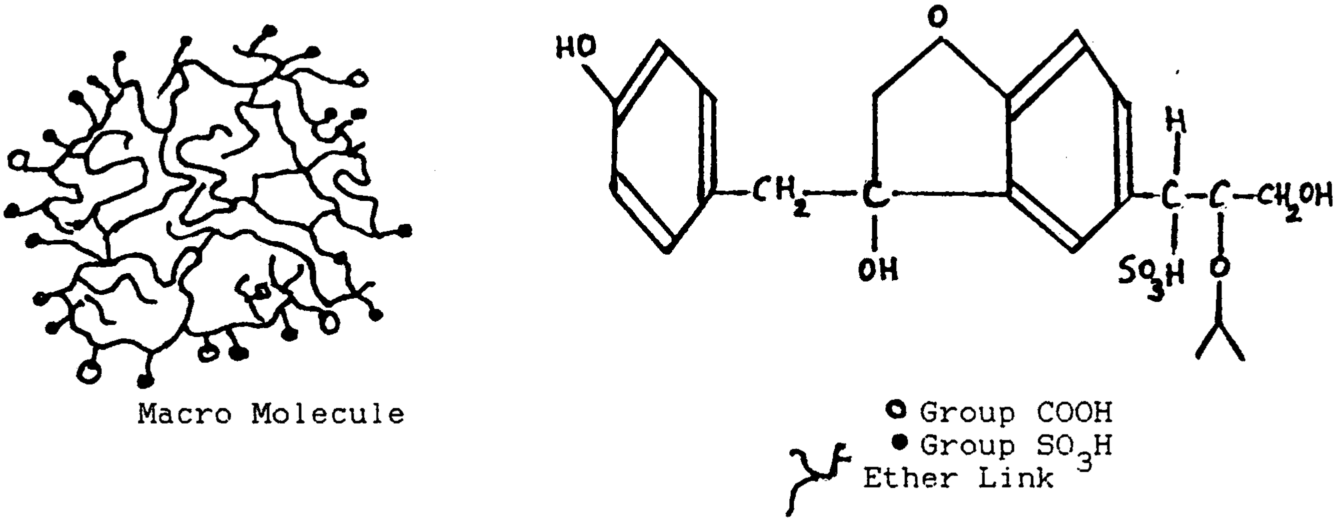


Fig. A.2 Schematic Representation of a Lignosulphonate Molecule

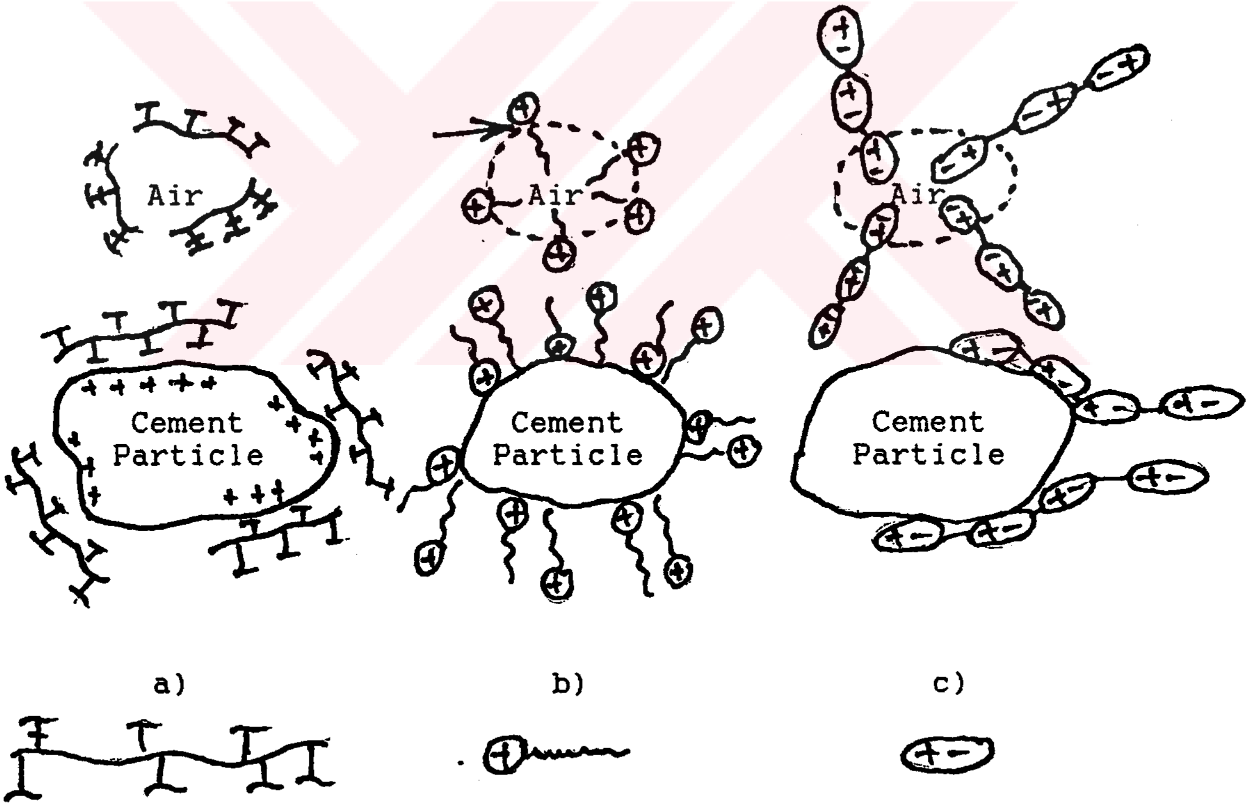


Fig. A.3 Mechanism of Action of Water Reducing Agent

a) anionic

b) cationic

c) non-ionic

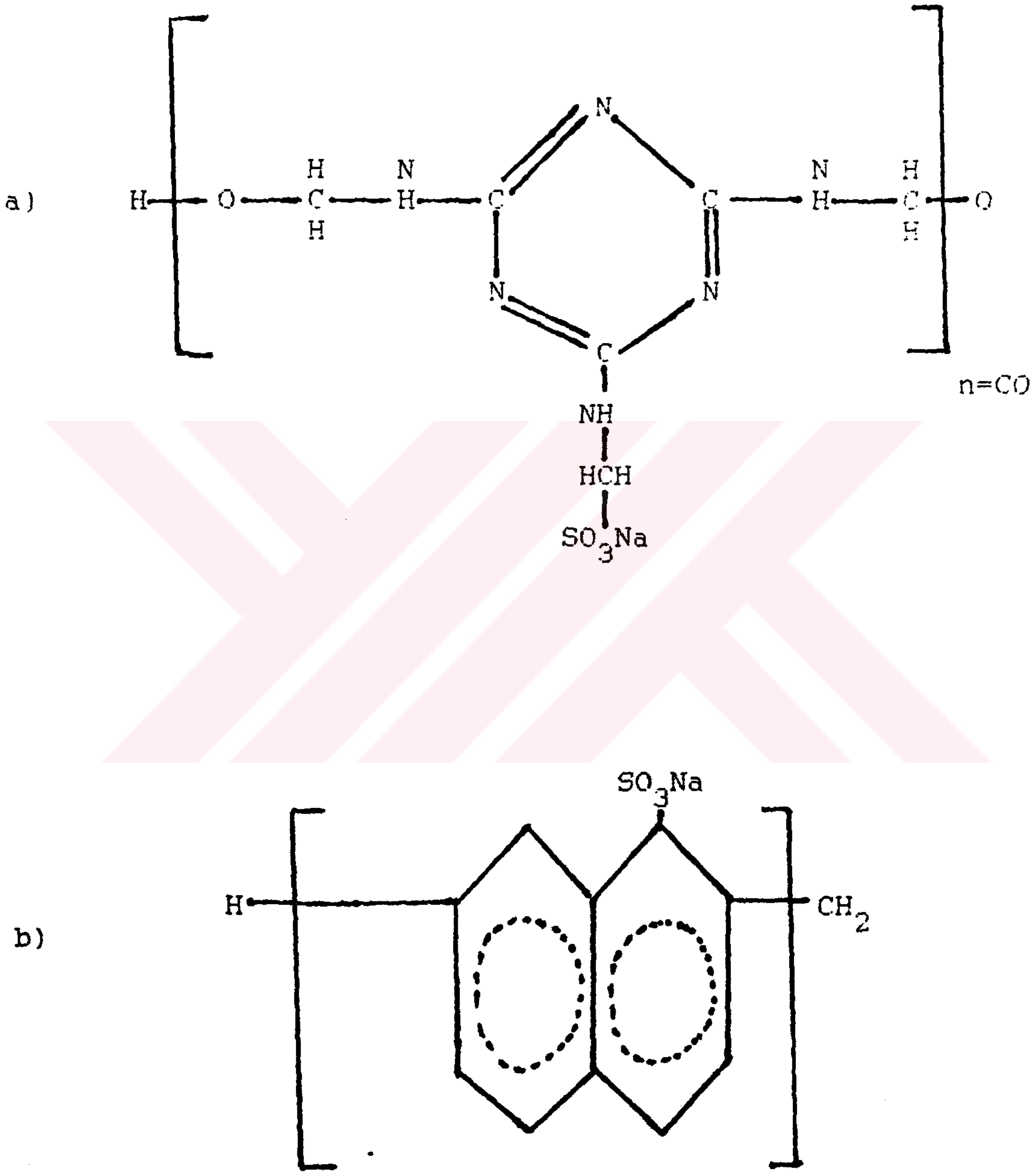


Fig. A.4 Schematic Representation of the Molecule of Two Commercial Superplasticizers

a) Melamine Sulphonate Formaldehyde Condensate

b) Naphthaline Sulphonate Formaldehyde Condensate

APPENDIX B

B.1. SIMPLE LINEAR REGRESSION

In the case of simple linear regression where there is a single independent regressor variable x and a single dependent random variable Y, the data may be represented by the pairs of observations $\{(x_i, y_i); i = 1, 2, \ldots, n\}$.

Similarly, using the estimated or fitted regression line

$$\hat{y} = a + b\,x\,,$$

each pair of observations satisfies the relation

$$y_i = a + b\,x_i + e_i$$

where $e_i = y_i - \hat{y}_i$ is called a residual and describes the error in the fit of the model at the ith data point.

For the sample, the least squares estimates **a** and **b** of the regression coefficients are computed from the formulas

$$b = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

$$a = \frac{\sum_{i=1}^{n} y_i - b\sum_{i=1}^{n} x_i}{n}$$

B.2. CORRELATION ANALYSIS

The independent regressor variable **x** is a physical or scientific variable but not a random variable. In fact **x** is measured with error. Therefore **Correlation Analysis** is necessary to measure the strength of relationships between two variables by means of a single number called a *Correlation Coefficient (r)*.

$$r = b\sqrt{\frac{S_{xx}}{S_{yy}}} = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}}$$

where

$$S_{xx} = \sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}$$

$$S_{yy} = \sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}$$

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n}$$

In *Multiple Linear Regression*, coefficient of correlation is calculated by

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

where $\hat{y}$ = estimated value from fitted regression line

y_{mean} = mean of observation

y = observation

B.3. NONLINEAR REGRESSION MODEL

A model in which x or y is transformed should be viewed as a *nonlinear regression model*. We normally refer to a regression model as linear when it is *linear in the parameters*. In other words, suppose the complexion of the data or other scientific information suggests that we should regress y^* against x^*, where each is a transformation on the natural variabiles x and y. Then the model of the form

$$y_i^*=\alpha+\beta x_i^*+\varepsilon_i$$

is a linear model since it is linear in the parameters α and β. The material given in *Section B.1.* and *B.2.* remains intact with y_i^* and x_i^* replacing y_i and x_i. A simple and useful example is the log-log model given by

$$\log y_i=\alpha+\beta \log x_i+\varepsilon_i$$

Although this model is not linear in x and y, it is linear in the parameters and is thus treated as a linear model. On the other hand, an example of a truly nonlinear model is given by

$$y_i=\beta_0+\beta_1 x^{\beta_2}+\varepsilon_i$$

where the parameters β_2 (as well as β_0 and β_1) is to be estimated. The model is not linear in β_2.

Table B.1 Some Useful Transformations to Linearize [8, p 388]

Functional Form Relating y to x	Proper Transformation	Form of Simple Linear Regression
Exponential:		
$y=\alpha e^{\beta x}$	$y^{*}=\ln y$	Regress y^{*} against x
Power:		
$y=\alpha x^{\beta}$	$y^{*}=\log y$; $x^{*}=\log x$	Regress y^{*} against x^{*}
Reciprocal:		
$y=\alpha+\beta(1/x)$	$x^{*}=1/x$	Regress y against x^{*}
Hyperbolic function:		
$y=x/(\alpha+\beta x)$	$y^{*}=1/y$; $x^{*}=1/x$	Regress y^{*} against x^{*}

B.4. f TEST

The regression sum of squares, SSR, and sum of square errors, SSE can be used to give some indication concerning whether or not the model is an adequate explanation of the true situation. One can test the hypothesis H_0 that the regression is not significant by merely forming the ratio

$$f=\frac{SSR/k}{SSE/(n-k-1)}=\frac{SSR/k}{s^2}$$

and rejecting H_0 at the α-level of significance when

$$f > f_\alpha(k, n-k-1)$$

Statistical analyses of the fitted relations in this work are given in *Table B.2.* A comparison of the correlation coefficients and f values with the critical values corresponding to α=0.01 level of significance (or 0.99 level of confidence) yields information about the "goodness of fit" of the relations adopted.

Table B.2 Statistical Analysis of Equations

Eq.	n	k	r(%)	SSE	SST	SSR
7.2	102	6	60.62	10675.3	27456.0	16644.09
7.3	102	6	67.65	11130.5	27456.0	18574.07
7.4	33	1	85.76	2.72901	15.7930	13.20080
7.5	103	4	75.98	189.372	796.450	605.1400
7.6.1	38	2	90.12	27.3220	274.713	247.5730
7.6.2	38	2	88.10	19.3904	162.282	142.8622
7.6.3	38	2	98.50	3.81360	246.339	242.5228
7.6.4	38	2	98.50	2.85834	186.183	183.3566
7.7	29	1	77.61	475.691	2124.11	1648.424
7.12	24	2	65.18	29.4644	84.6292	55.16470
7.13	24	2	62.98	19.8453	53.6044	33.75900
7.14	24	2	75.87	14217.1	58923.8	44705.95
7.15	29	1	97.67	104.378	2124.11	2074.546
7.16	29	1	93.22	317.196	2858.98	2665.200
7.17	29	1	95.11	103.943	2124.11	2020.182
7.18	29	1	98.66	146.582	2124.11	2095.670
7.19	29	1	95.23	320.208	2124.11	2022.790
7.20	29	1	93.19	144.586	2124.11	1979.526
7.21	29	1	99.70	149.640	2858.98	2850.387
7.22.1	29	1	78.05	466.336	2124.11	1657.785
7.22.2	29	1	78.03	4.58607	20.8891	16.29999
7.23.1	29	1	96.83	483.050	2124.11	2056.796
7.23.2	29	1	98.88	5.63145	29.5694	29.23735
7.24	28	1	77.88	469.776	2124.11	1654.247
7.25	27	1	96.26	141.971	1377.78	1326.238
7.26	29	1	89.30			
7.27	29	1	63.40	777.322	2124.11	1346.716
7.28	29	2	80.87	406.341	2124.11	1717.739
7.29	29	3	80.89	405.995	2124.11	1717.658
7.30	29	2	84.46	329.894	2124.11	1794.105
7.31	29	2	98.89	0.06178	6.04704	5.979783
7.32	29	2	98.98	152.042	2124.11	2102.448
7.33	27	2	90.54	130.636	1377.78	1247.466
7.34	29	2	79.75	430.363	1693.89	2124.114
7.35	29	2	78.67	452.848	1671.06	2124.114
7.36	29	2	73.48	563.139	1560.88	2124.114
7.37	29	2	73.31	567.027	1557.14	2124.114
7.38	29	2	74.65	538.532	1585.75	2124.114
7.39	29	2	74.57	540.148	1583.96	2124.114

where n ≡ number of observation

n-k-1 ≡ degrees of freedom

k ≡ number of distinc variables

k+1 ≡ number of coefficient

Table B.3 f-test of Equations

Eq.	f	k	n-k-1	$f_{0.01}(k,n-k-1)$	Form
7.2	24.686	6	95	3.12	Polynomial
7.3	26.420	6	95	3.12	Polynomial
7.4	149.95	1	31	7.56	Power
7.5	78.290	4	98	3.48	Polynomial
7.6.1	158.57	2	35	5.39	Polynomial
7.6.2	128.91	2	35	5.39	Polynomial
7.6.3	667.74	2	21	5.78	Polynomial
7.6.4	673.55	2	21	5.78	Polynomial
7.7	93.564	1	27	7.68	Hyperbolic
7.12	19.659	2	21	5.78	Polynomial
7.13	17.862	2	21	5.78	Polynomial
7.14	40.879	2	26	5.53	Polynomial
7.15	536.63	1	27	7.68	Linear
7.16	226.86	1	27	7.68	Power
7.17	524.76	1	27	7.68	Linear
7.18	386.02	1	27	7.68	Linear
7.19	256.40	1	27	7.68	Power
7.20	369.66	1	27	7.68	Linear
7.21	514.30	1	27	7.68	Linear
7.22.1	95.983	1	27	7.68	Linear
7.22.2	95.964	1	27	7.68	Linear
7.23.1	114.97	1	27	7.68	Power
7.23.2	140.18	1	27	7.68	Power
7.24	95.076	1	27	7.68	Linear
7.25	252.22	1	25	7.77	Power
7.27	46.778	1	27	7.68	Linear
7.28	54.955	2	26	5.53	Polynomial
7.29	35.256	3	25	4.68	Polynomial
7.30	70.700	2	26	5.53	Linear
7.31	1258.2	2	26	5.53	Linear
7.32	179.77	2	26	5.53	Exponential
7.33	114.59	2	24	5.61	Power
7.34	51.167	2	26	5.53	Linear
7.35	47.971	2	26	5.53	Linear
7.36	36.032	2	26	5.53	Linear
7.37	35.700	2	26	5.53	Linear
7.38	38.280	2	26	5.53	Linear
7.39	38.122	2	26	5.53	Linear

	CLASS	%	RATIO	kg	kg	kg	A0 kg	A1 kg	A2 kg	A3 kg	Modulus K19	SLUMP mm	VeBe t s
Aug,9	C14	0.0	0.578	180.6	0.00	312.3	106.8	849.2	376.0	593.7	4.575	80	3.33
Aug,9	C14	0.0	0.578	180.2	0.00	311.7	106.6	847.6	375.3	592.6	4.575	70	3.69
Aug,10	C14	0.5	0.579	165.9	1.43	286.7	111.1	885.7	345.4	591.6	4.566	80	3.69
Aug,10	C14	0.5	0.579	166.8	1.44	288.1	111.6	890.1	347.1	594.5	4.566	100	2.18
Aug,11	C14	2.0	0.579	145.8	5.03	251.6	113.3	887.7	305.1	566.1	4.554	200	1.31
Aug,11	C14	2.0	0.579	145.8	5.03	251.6	113.3	887.7	305.1	566.1	4.554	170	1.93
Aug,18	C14	5.0	0.579	145.0	12.51	250.3	113.8	891.3	299.5	561.6	4.541	165	1.85
Aug,31	C14	5.0	0.579	144.1	12.43	248.7	113.0	885.6	297.6	558.0	4.542	140	2.16
Aug,22	C16	0.0	0.540	181.5	0.00	336.1		1080.6	220.3	609.4	4.427	60	3.92
Aug,22	C16	0.0	0.540	181.0	0.00	335.2		1077.7	219.7	607.9	4.427	60	4.05
Sep,16	C16	2.0	0.541	143.0	5.29	264.5		1086.2	178.1	568.8	4.485	150	1.86
Aug,16	C20	0.0	0.452	192.6	0.00	425.7		930.2	266.7	599.6	4.393	85	3.53
Aug,16	C20	0.0	0.453	192.6	0.00	425.6		930.2	266.7	599.6	4.393	85	3.26
Aug,17	C20	0.5	0.450	169.0	1.88	375.7		1031.3	249.2	597.7	4.410	85	3.11
Aug,17	C20	0.5	0.450	167.7	1.86	372.8		1023.4	247.3	593.1	4.418	95	2.35
Aug,24	C20	2.0	0.450	137.2	6.10	304.8		1043.8	207.9	564.6	4.452	160	1.96
Aug,25	C20	2.0	0.450	138.8	6.17	308.4		1055.9	210.3	571.1	4.451	115	2.35
Sep,16	C20	5.0	0.450	122.5	13.62	272.3		993.5	184.3	526.8	4.456	100	2.77
Aug,23	C25	0.0	0.402	186.5	0.00	463.4		851.0	309.1	612.9	4.422	70	2.94
Aug,24	C25	0.0	0.402	186.5	0.00	463.4		851.0	309.1	612.9	4.422	85	2.55
Aug,29	C25	2.0	0.395	140.5	7.13	355.4		1012.0	242.4	583.0	4.433	60	3.31
Sep,2	C25	2.0	0.400	141.6	7.08	354.0		1005.1	240.8	579.1	4.433	60	3.40
Aug,31	C30	0.0	0.381	185.4	0.00	487.1		814.5	324.4	613.6	4.411	80	2.80
Sep,1	C30	0.0	0.380	184.2	0.00	484.1		809.5	322.4	609.8	4.411	130	2.16
Sep,1	C30	0.5	0.380	169.6	2.23	446.3		923.9	280.3	582.1	4.342	90	2.55
Aug,19	C30	2.0	0.380	139.1	7.33	366.3		981.0	247.1	567.3	4.409	95	2.43
Aug,23	C30	2.0	0.380	137.0	7.21	360.7		965.9	243.3	558.6	4.409	120	2.06
Aug,25	C30	5.0	0.383	123.6	16.14	322.8		870.2	232.8	556.9	4.520	145	2.08
Aug,29	C30	5.0	0.383	125.6	16.40	327.9		884.1	236.5	565.8	4.520	145	2.06

O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
FRESH CONCRETE					H		R	D	E	N	E	D	
A pr %	A gr %	Dexp kg/m^ 3	fc cyl	fc cube 200 mm	fc cube 150 mm	f st	f flex	Ncyl	NcubeE 150 mm	NcubeT 150 mm	NcubeB 150 mm	NcubeE 200 mm	NcubeT 200 mm
1.33	0.41	2311.8	17.18	20.93	22.65	2.205	3.533	30.5	33.8	30.2	30.6	33.1	29.6
1.43	0.61	2307.4	18.57	21.38	22.41	2.276	3.493	30.3	32.8	31.7	30.3	33.8	31.0
2.63	2.23	2276.7	19.47	22.30	24.63	2.578	3.741	31.5	33.4	32.8	30.3	32.2	32.3
2.83	1.74	2288.1	18.75	20.49	24.53	2.503	3.979	31.5	34.4	33.3	32.0	34.3	31.5
7.03	7.34	2161.3	12.83	14.90	18.17	1.632	3.124	27.4	30.0	29.4	29.5	29.8	28.6
7.73	7.34	2161.3	13.26	15.87	17.13	1.650	2.463	28.2	28.3	30.2	26.7	29.7	30.4
	7.05	2160.3	6.31	7.11	8.60	0.797	2.177	21.5	23.5	25.4	21.9	23.6	24.7
	7.64	2146.5	7.31	8.26	8.02	0.864	1.910	22.7	21.6	24.1	22.8	21.3	22.0
1.28	0.83	2407.8	22.53	23.41	27.83	2.633	3.413	34.3	36.9	34.7	34.1	35.9	37.6
1.63	1.10	2401.4	21.49	22.48	26.06	2.309	3.684	34.2	38.2	36.7	35.8	36.2	35.6
8.13	8.67	2245.9	14.62	16.59	16.52	1.647	2.864	29.9	29.2	29.5	28.2	30.8	28.8
1.23	0.02	2422.9	23.39	30.47	34.44	2.570	3.677	36.0	38.0	36.3	35.9	33.1	29.6
1.13	0.02	2422.9	25.00	32.38	35.79	2.720	3.802	35.7	36.8	35.7	37.6	33.8	31.0
2.43	1.10	2424.7	26.02	30.81	34.72	2.755	3.700	36.7	36.9	37.5	36.5	39.2	38.6
2.73	1.86	2406.2	26.13	32.56	35.76	2.899	4.256	34.6	36.4	36.3	35.3	37.7	38.6
8.13	8.51	2264.4	15.74	19.80	21.64	1.957	3.021	29.8	31.7	32.0	29.0	31.9	30.5
6.90	7.45	2290.6	17.77	22.69	23.41	1.968	3.414	30.7	32.5	33.4	32.1	31.6	34.3
	14.54	2113.1	6.51	8.62	10.96	0.959	2.606	23.8	26.6	26.7	23.9	26.4	27.4
1.03	0.21	2432.8	26.04	32.83	40.15	3.126	4.100	37.6	40.7	38.7	40.4	40.4	35.1
0.93	0.61	2423.0	26.49	35.40	37.36	3.004	3.902	33.8	39.8	39.0	41.1	39.9	40.2
5.43	5.66	2341.3	21.64	26.64	21.64	2.224	3.804	36.3	37.8	36.9	35.2	37.5	36.1
5.93	6.09	2327.6	21.67	26.24	21.31	2.493	4.653	35.7	37.5	37.6	34.5	36.0	37.6
0.93	0.72	2425.0	32.47	36.11	38.35	2.759	3.838	38.6	40.3	38.9	39.2	38.2	38.9
1.33	1.34	2410.1	32.22	34.38	38.32	2.743	5.202	36.3	38.3	34.7	38.7	37.2	36.7
2.13	2.14	2404.4	33.18	35.84	41.26	3.253	5.825	38.0	39.6	41.5	39.4	41.3	41.8
7.13	7.01	2308.1	24.14	23.26	28.60	1.286	3.655	35.9	37.2	36.6	36.8	39.1	38.2
8.23	8.44	2272.6	22.29	23.75	28.48	1.254	4.015	33.4	34.6	36.3	31.8	33.2	35.9
	14.30	2122.4	0.46	0.56	1.22	0.070	0.000	0.0	0.0	0.0	0.0	0.0	0.0
	12.93	2158.3	0.39	1.25	2.22	0.194	1.325	0.0	0.0	0.0	0.0	0.0	0.0

AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM
C	O	N	C	R	T	E				
NumbeB 200 mm	Voyl H	Voyl A	Voube 150 mm	Voubell 150 mm	Voube 200 mm	Voubell 200 mm	KG	KGM	KF	Vall m^3
33.7	4.519	4.415	4.567	4.582	4.505	4.544	7.231	7.223	134.798	0.004124
31.8	4.646	4.628	4.654	4.532	4.475	4.530	6.689	6.686	147.626	0.006054
30.8	4.568	4.616	4.555	4.571	4.609	4.534	6.358	6.364	176.568	0.023485
32.2	4.580	4.535	4.581	4.591	4.556	4.536	6.602	6.602	164.236	0.018606
28.6	4.287	4.099	4.392	4.335	4.056	4.069	9.649	9.622	175.952	0.077562
27.3	4.287	4.099	4.211	4.240	4.165	4.259	9.336	9.310	181.849	0.077562
23.1	3.594	3.414	3.892	3.910	3.719	3.689	19.618	19.578	88.674	0.080946
20.3	3.876	3.805	3.690	3.791	3.587	3.654	16.935	16.890	107.080	0.086821
	4.451	4.433	4.622	4.577	4.539	4.564	6.317	6.316	166.573	0.008248
34.8	4.442	4.500	4.547	4.451	4.530	4.644	6.623	6.622	161.715	0.010895
27.3	4.290	4.349	4.182	4.247	4.219	4.138	9.699	9.690	199.624	0.091111
33.7	4.678	4.668	4.700	4.760	4.710	4.757	8.684	8.668	132.309	0.000100
31.8	4.769	4.727	4.824	4.770	4.618	4.738	8.089	8.106	141.545	0.000207
37.0	4.685	4.600	4.831	4.797	4.585	4.672	7.876	7.881	158.940	0.012559
37.0	4.695	4.697	4.717	4.758	4.579	4.630	7.843	7.847	167.820	0.020140
28.5	4.208	4.152	4.255	4.233	4.154	4.197	13.020	12.996	168.469	0.090182
28.8	4.458	4.282	4.405	4.350	4.324	4.305	11.533	11.516	177.064	0.079624
24.2	3.861	3.658	3.904	3.893	3.879	3.815	31.481	31.418	110.680	0.156801
42.7	4.755	4.677	4.857	4.793	4.758	4.639	9.813	9.835	130.547	0.002035
40.6	4.603	4.497	4.646	4.662	4.626	4.551	10.075	10.051	130.851	0.006119
34.3	4.662	4.458	4.624	4.491	4.456	4.443	12.290	12.260	162.685	0.062802
35.0	4.588	4.460	4.557	4.562	4.476	4.528	11.969	11.958	168.945	0.066751
39.2	4.725	4.628	4.619	4.536	4.530	4.548	8.805	8.822	157.747	0.007223
38.7	4.682	4.528	4.557	4.496	4.481	4.634	8.920	8.895	162.085	0.013390
39.0	4.830	4.602	4.752	4.760	4.668	4.619	8.662	8.659	177.929	0.023242
37.0	4.611	4.434	4.403	4.516	4.438	4.467	11.905	11.908	187.923	0.076242
31.9	4.453	4.312	4.508	4.529	4.498	4.487	12.894	12.869	190.007	0.090394
0.0	1.373	1.135	1.775	1.508	1.489	1.356	624.774	613.793	6.099	0.156393
0.0	2.223	1.307	1.241	1.519	0.869	0.787	796.913	723.601	4.759	0.142916

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
DATE	CONC CLASS	SP %	W/C RATIO	WATER kg	SP CON kg	CEMENT kg	AGGREGATES				Fineness Modulus Kf9	FRESH CONCRETE				
							A0 kg	A1 kg	A2 kg	A3 kg		SLUMP mm	VeBe t s	A pr %	A gr %	Dexp kg/m^3
Feb,9	C14	0.00	0.533	163.4		306.6		984.4	418.6	530.5	4.692	125			0.19	2456.5
Feb,11	C14	0.00	0.648	193.8		298.9		1040.5	231.8	605.8	4.550	70			1.30	2370.8
Feb,15	C14	0.00	0.618	192.5		311.4		988.1	308.7	570.2	4.570	70			1.69	2365.6
Jun,9	C14	0.00	0.476	188.2		395.2	93.0	771.1	470.8	617.6	4.597	70	3.24	1.03	0.39	2442.9
Jun,21	C14	0.00	0.582	189.9		326.5	110.9	888.4	393.1	620.3	4.574	75	3.36	1.48	0.42	2418.2
Jun,21	C14	0.25	0.604	183.9	0.80	304.4	118.8	941.7	367.9	628.2	4.565	70	3.78	1.73	0.46	2426.1
Jun,22	C14	0.25	0.566	178.5	0.80	315.4	114.4	912.7	385.6	626.2	4.578	70	4.45	1.83	0.37	2418.3
Jun,22	C14	0.25	0.581	178.1	0.77	306.8	117.3	931.8	375.7	628.5	4.574	65	4.05	2.13	0.40	2421.6
Jun,23	C14	0.50	0.615	177.2	1.44	288.3	120.5	951.6	348.8	620.9	4.560	60	4.68	2.73	2.98	2388.6
Jun,23	C14	0.50	0.599	180.1	1.51	300.6	118.9	941.8	362.1	624.8	4.562	70	3.43	2.33	3.88	2410.9
Jun,23	C14	0.50	0.580	175.5	1.51	302.6	118.0	935.4	365.4	624.0	4.564	80	2.77	2.13	3.30	2404.4
Jun,24	C14	1.00	0.604	173.2	2.87	286.8	119.7	945.0	346.4	616.6	4.559	125	2.33	3.73	2.12	2370.8
Jun,27	C14	1.00	0.580	169.6	2.93	292.6	117.9	933.1	353.1	615.6	4.561	85	3.86		1.65	2366.9
Jun,28	C14	1.00	0.579	165.6	2.86	285.8	118.4	937.1	360.5	614.8	4.576	70	3.89	3.88	1.43	2366.6
Jun,28	C14	1.50	0.578	160.8	4.18	278.0	120.2	945.3	335.4	610.1	4.555	75	4.15	5.48	3.26	2333.9
July,1	C14	2.00	0.612	158.3	5.18	258.8	121.6	951.7	316.0	601.3	4.556	85	2.67	6.83	1.44	2291.2
July,1	C14	2.00	0.578	155.9	5.39	269.6	120.5	946.4	324.9	604.3	4.552	70	2.69	5.88	1.12	2306.5
July,4	C14	5.00	0.627	146.1	11.66	233.1	119.2	932.3	299.5	583.0	4.576	60	2.97	9.23	5.05	2205.8
July,5	C14	5.00	0.578	149.5	12.94	258.7	116.7	914.3	308.9	581.1	4.547	80	2.67	8.23	4.26	2225.4
Feb,21	C16	0.00	0.552	200.0		362.3		962.0	300.5	555.1	4.458	145			0.88	2380.0
Feb,21	C16	0.00	0.534	194.1		363.6		965.2	301.5	557.0	4.457	90			1.20	2301.4
Feb,21	C16	0.00	0.504	184.1		365.2		969.6	302.9	559.5	4.458	75			1.84	2301.4
July,28	C16	0.00	0.540	181.6		336.3		1081.5	219.7	589.6	4.426	65	3.33	1.43	0.79	2408.7
July,27	C16	0.25	0.525	174.2	0.83	331.9		1094.3	217.4	592.4	4.430	75	2.84	1.53	1.10	2411.1
July,28	C16	0.25	0.540	174.1	0.81	322.5		1098.3	215.9	592.5	4.443	65	3.04	1.53	1.33	2404.1
July,27	C16	0.50	0.573	174.8	1.62	304.0		1116.2	202.3	587.5	4.447	50	3.11	2.08	1.79	2387.2
July,27	C16	0.50	0.540	172.4	1.60	319.2		1108.0	210.4	591.5	4.438	90	3.04	2.63	1.42	2403.0
July,27	C16	0.50	0.540	169.4	1.57	313.7		1118.2	207.4	592.7	4.442	75	2.84	2.13	1.59	2403.0
July,27	C16	1.00	0.540	161.8	3.00	299.5		1124.5	199.0	587.8	4.450	60	3.24	3.23	2.95	2375.7
July,25	C16	1.50	0.530	153.8	4.24	290.1		1117.2	193.1	580.0	4.453	75	2.53	4.73	4.72	2338.5
July,25	C16	- 1.50	0.540	152.0	4.23	281.5		1114.3	188.0	574.6	4.457	75	2.65	5.43	5.68	2314.7
July,21	C16	2.00	0.540	143.7	5.32	266.1		1127.1	179.2	571.5	4.467	60	2.79	6.13	6.08	2292.9
July,11	C16	5.00	0.528	143.8	13.18	272.1	113.6	896.8	328.7	585.1	4.559	85	2.26	8.23	4.28	2239.8
July,11	C16	5.00	0.540	130.8	12.11	242.3		1087.0	166.4	545.7	4.480	90	2.02	9.43	11.29	2184.3

July, 19	C16	5.00	0.532	129.3	11.95	243.2		1111.5	163.9	552.5	4.474	75	3.31	7.93	10.36	2212.3
July, 20	C16	5.00	0.546	130.5	12.33	244.5	116.1	909.9	302.1	574.9	4.562	75	2.77	8.98	7.04	2177.2
Mar, 2	C20	0.00	0.498	213.4		428.1		924.1	288.7	533.3	4.309	65			0.82	2387.6
Mar, 23	C20	0.00	0.552	193.9		351.4		1020.5	217.8	607.4	4.452	70			0.754	2391.1
Mar, 23	C20	0.00	0.455	190.1		417.6		923.6	263.6	592.2	4.397	70			1.47	2306.9
July, 29	C20	0.00	0.452	206.1		455.0		922.0	263.2	591.3	4.327	75	2.87	1.53	1.28	2438.3
May, 30	C20	0.25	0.488	175.7	0.90	359.7		1039.3	240.8	592.2	4.427	60			1.32	2407.8
May, 30	C20	0.25	0.450	175.4	0.97	389.9		998.5	257.2	591.2	4.405	100			1.31	2412.3
May, 31	C20	0.25	0.473	182.4	0.96	385.5		1011.2	258.1	594.0	4.412	70			0.15	2431.3
Jun, 1	C20	0.25	0.450	175.4	0.97	389.8		1012.3	261.3	597.0	4.411	70	4.85	1.73	0.43	2436.0
Jun, 2	C20	0.50	0.475	178.7	1.89	376.5		1035.2	250.4	598.9	4.417	80	4.41	1.98	0.13	2441.5
Jun, 3	C20	0.50	0.443	167.0	1.85	376.6		1025.6	253.3	597.8	4.423	75	3.66	2.03	1.33	2422.2
Jun, 3	C20	0.50	0.450	169.9	1.89	377.6		1038.1	251.1	600.5	4.417	75	4.55	1.88	0.52	2439.1
May, 18	C20	1.00	0.469	154.1	3.20	328.4		1070.2	222.4	587.8	4.445	85			3.91	2366.3
May, 27	C20	1.00	0.449	153.9	3.42	342.8		1053.3	233.0	591.3	4.443	75			3.36	2383.9
May, 27	C20	1.00	0.450	152.2	3.38	338.2		1063.3	230.9	592.5	4.445	75			3.55	2380.5
Jun, 6	C20	1.50	0.469	153.2	4.90	326.6		1062.1	220.7	583.3	4.443	105	3.24	5.28	4.46	2350.7
Jun, 6	C20	1.50	0.450	149.3	4.98	331.7		1067.6	224.1	588.3	4.442	60	4.56	4.68	4.17	2365.9
May, 17	C20	2.00	0.450	139.7	6.21	310.5		1062.6	211.1	575.3	4.452	75			6.05	2305.4
May, 17	C20	5.00	0.391	149.9	16.66	383.5		959.8	247.3	568.3	4.389	180			5.34	2325.3
Mayy, 17	C20	5.00	0.445	128.2	12.88	287.8		1022.8	194.2	546.0	4.452	75			11.30	2191.7
May, 17	C20	5.00	0.450	128.8	14.31	286.2		1043.9	193.6	553.3	4.455	60			10.21	2220.2
Mar, 2	C25	0.00		205.0		518.7		868.5	271.5	501.3	4.097	70			1.77	2364.8
Mar, 24	C25	0.00	0.470	183.5		390.1		947.9	222.1	647.5	4.481	70			1.60	2391.1
Mar, 24	C25	0.00	0.415	186.3		449.3		849.7	308.0	612.2	4.448	70			1.20	2405.6
July, 8	C25	0.25	0.400	176.2	1.10	440.6		921.6	291.0	591.6	4.382	60	3.76	1.53	1.11	2422.0
July, 7	C25	0.50	0.418	172.8	2.07	413.4		968.4	276.5	596.6	4.403	60	3.99	1.73	0.86	2429.7
July, 7	C25	0.50	0.415	172.6	2.08	415.8		951.9	277.4	595.2	4.405	60	4.08	1.93	1.43	2414.9
July, 7	C25	0.50	0.400	170.9	2.14	427.2		933.9	283.4	589.4	4.389	65	3.63	1.73	1.88	2407.2
July, 6	C25	1.00	0.400	158.2	3.96	395.6		991.0	266.1	596.0	4.414	70	3.43	3.28	2.30	2410.8
July, 6	C25	1.50	0.400	149.1	5.60	372.0		999.5	252.1	587.1	4.424	60	3.69	4.88	4.35	2366.2
July, 5	C25	2.00	0.400	142.5	7.13	356.3		1011.3	242.0	582.8	4.432	60	3.33	5.78	5.50	2342.0
July, 5	C25	5.00	0.400	134.4	16.81	336.1		1000.4	226.9	565.8	4.434	70	2.37	7.53	7.74	2280.6
Mar, 18	C30	0.00	0.367	219.6		598.1		846.3	260.0	469.9	3.901	70			1.18	2364.8
Mar, 23	C30	0.00	0.477	193.8		405.9		923.7	266.4	597.9	4.429	85			0.83	2396.6
Mar, 24	C30	0.00	0.449	185.2		412.4		889.9	294.2	616.3	4.487	70			1.39	2398.0
Mar, 24	C30	0.00	0.396	185.6		469.0		814.2	324.1	613.5	4.444	70			1.33	2406.3
May, 12	C30	0.25	0.380	186.1	1.09	434.0		940.5	291.2	598.9	4.396	60			1.46	2430.7

May, 12	C30	0.50	0.380	162.9	2.14	428.3		948.0	287.6	598.6	4.399	60			1.63	2427.5
May, 11	C30	1.00	0.399	154.6	3.87	387.3		981.2	263.4	590.1	4.421	70			3.62	2380.5
May, 11	C30	1.00	0.380	154.5	4.06	406.1		960.2	274.2	591.6	4.410	75			3.33	2390.7
May, 12	C30	1.50	0.380	145.5	5.74	382.4		980.4	263.4	589.6	4.430	70			4.60	2366.8
Mar, 31	C30	2.00	0.393	149.0	7.60	379.3		922.9	274.0	614.0	4.510	70			5.05	2346.0
May, 10	C30	2.00	0.374	146.1	7.81	390.6		949.9	265.5	580.3	4.417	170			5.49	2340.2
May, 10	C30	2.00	0.405	139.8	6.91	345.5		1021.8	236.1	572.3	4.425	70			6.35	2322.5
May, 11	C30	2.00	0.381	142.0	7.46	373.1		995.6	250.2	576.3	4.407	70			5.50	2344.7
May, 13	C30	3.00	0.380	134.3	10.60	353.2		973.4	240.4	567.4	4.431	70			8.17	2279.4
May, 13	C30	4.00	0.380	133.3	14.02	350.5		975.4	237.9	565.9	4.430	60			8.15	2277.0
Mar, 30	C30	5.00	0.455	134.0	14.72	294.4		1000.2	214.7	594.7	4.548	70			8.73	2252.7
Mar, 30	C30	5.00	0.383	134.2	17.52	350.1		944.8	252.7	604.6	4.520	65			6.97	2303.9

APPENDIX D

D.1. SIMPLE SIMPLEX ALGORITHM FOR A CONCRETE PROBLEM

Let X1 ≡ Weight of Cement (δ_{X1}=3.13)

X2 ≡ Weight of Water (δ_{X2}=1.00)

X3 ≡ Weight of Sand (δ_{X3}=2.50)

X4 ≡ Weight of Coarse Aggregate (δ_{X4}=2.65)

and cost of materials are 4.40, 0.02, 0.40 and 0.65 respectively.

Grading Limits

Let upper grading limit is

$$X3 - 0.46X4 \geq 0$$

and lower grading limit is

$$-X3 + 0.532X4 \geq 0$$

Workability

$$X2 \geq 0.218X1 + 0.125X3 + 0.054X4$$

Strength

$$\frac{X2}{X1} \geq 0.5$$

Durability

$$X1 \geq 300$$

Volumetric

$$0.32X1 + X2 + 0.40X3 + 0.377X4 = 980$$

Objective Function

$$F = 4.40X1 + 0.02X2 + 0.40X3 + 0.65X4$$

From workability and grading constraints, we can write

$$X2 = 980 - (0.32X1 - 0.40X3 - 0.377X4)$$

$$X3 = 0.46X4$$

substituiting these equations into other constraints:

$$0.538X1 + 0.6725X4 \leq 980$$

$$1.64X1 + 1.122X4 \geq 1960$$

$$X1 \geq 300$$

$$4.406X1 + 0.84522X4 = F - 19.6 = z_{min}$$

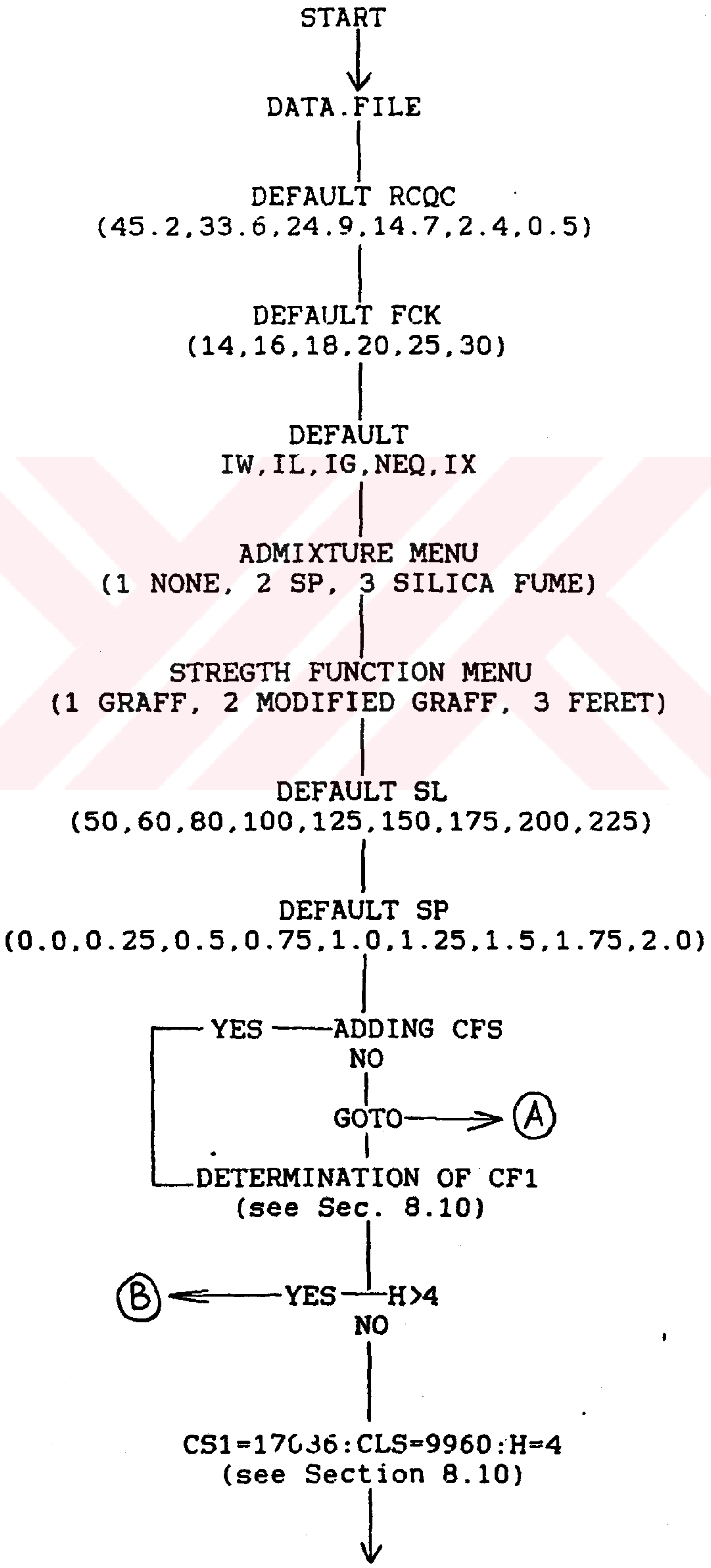
Simplex Tableau

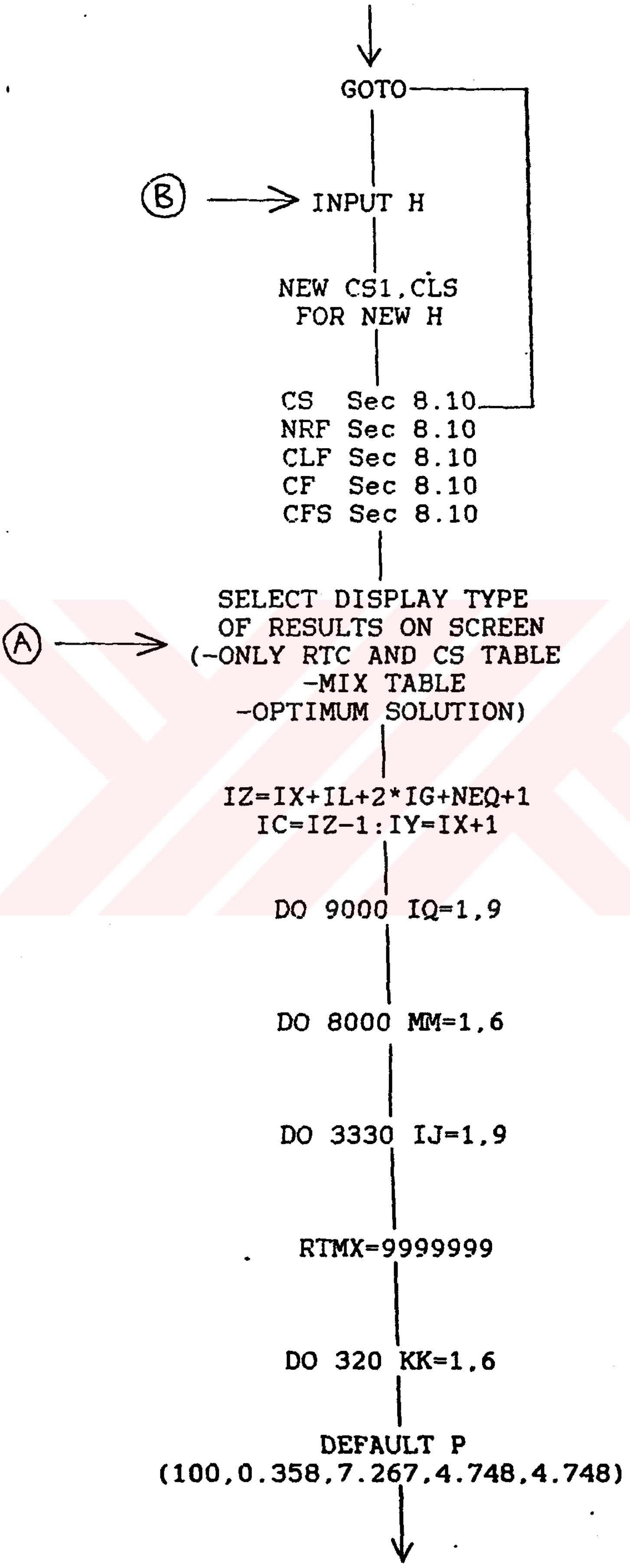
	X1	X4	S1	A1	A2	S2	S3	Constants
X5	0.538	0.6725	1					980
X6	1.64	1.122		1		-1		1960
X7	1				1		-1	300
-z	4.4064	0.84522						0
-w	-3.178	-1.7945						-3240
X5	0	0.6725	1		-0.538		0.538	818.6
X6	0	1.122		1	-1.64		1.64	1468
X1	1				1		-1	300
-z	0	0.84522			-4.406		4.406	-1321.92
-w	0	-1.7945			3.178		-3.18	-2286.6
X4	0	1	1.487		-0.80		0.80	1217.25
X6	0	0	-1.668	1	-0.742		0.742	102.25
X1	1	0			1		-1	300
-z	0	0	-1.257		-3.73		3.73	-2350.74
-w	0	0	2.668		1.742		-1.74	-102.24
X4	0	1	3.285	-1078	0		0	1107
X9	0	0	-2.248	1.348	-1		1	138
X1	1	0	-2.248	1.348	0		0	438
-z	0	0	7.128	-5.03	0		0	-2864.73

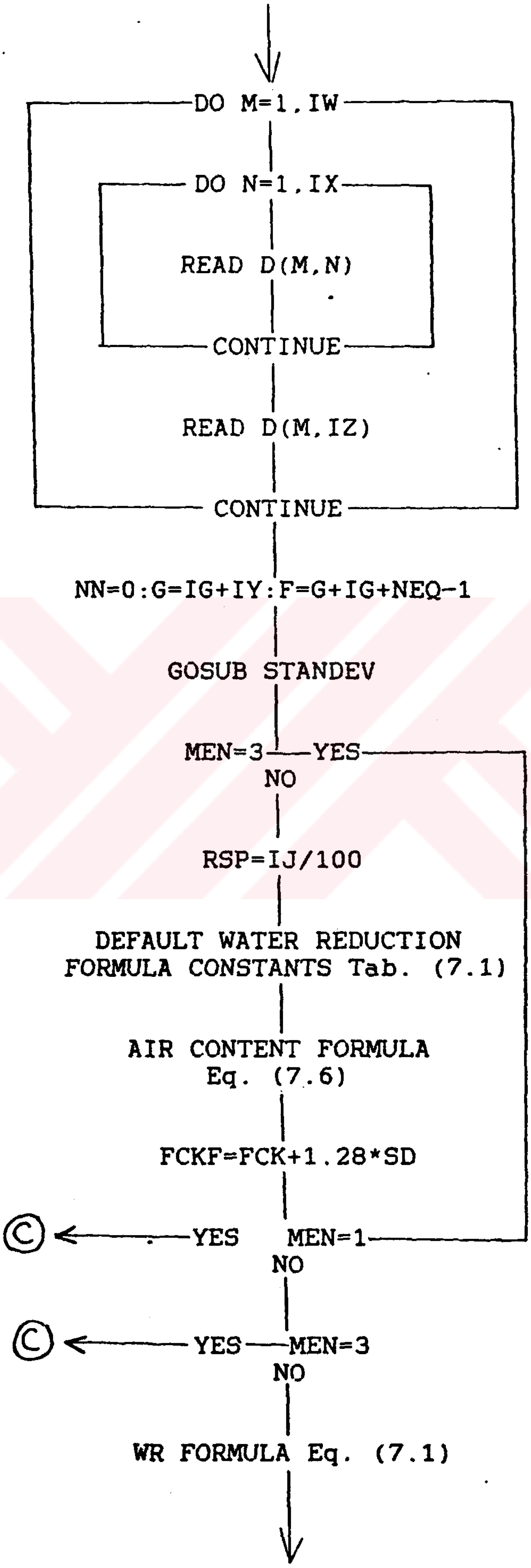
Result: X1=438. X4=1107 and

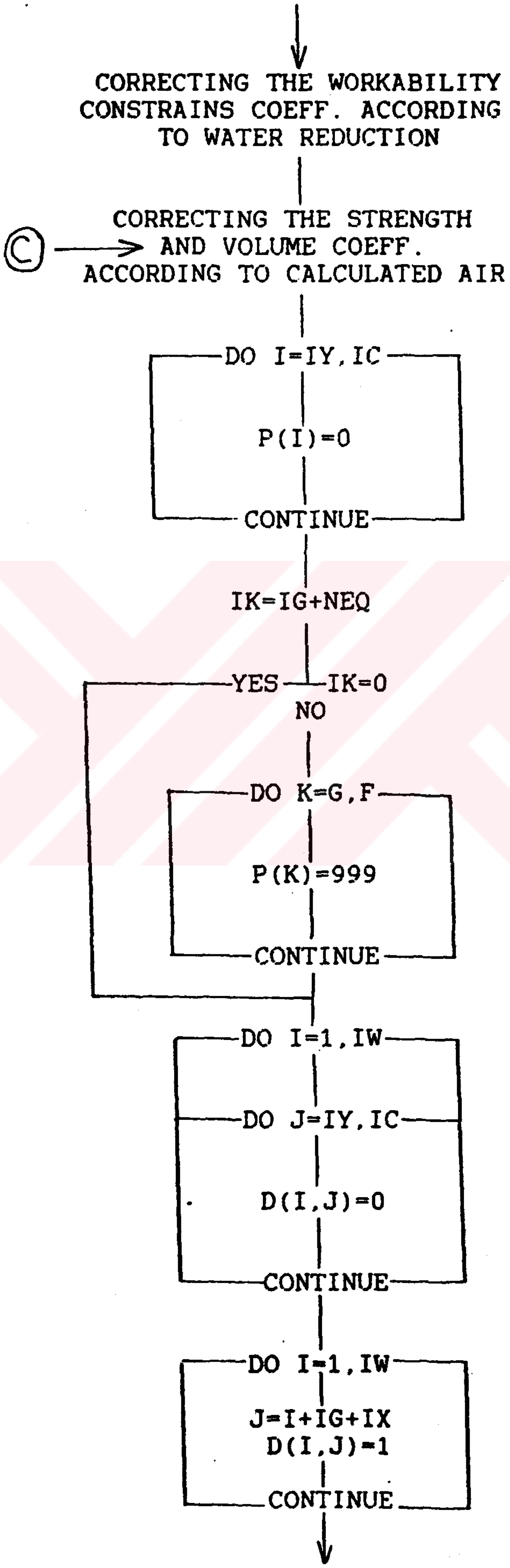
$$F_{min} = Z_{min} + 19.6 = 2864.73 + 19.6 = 2884$$

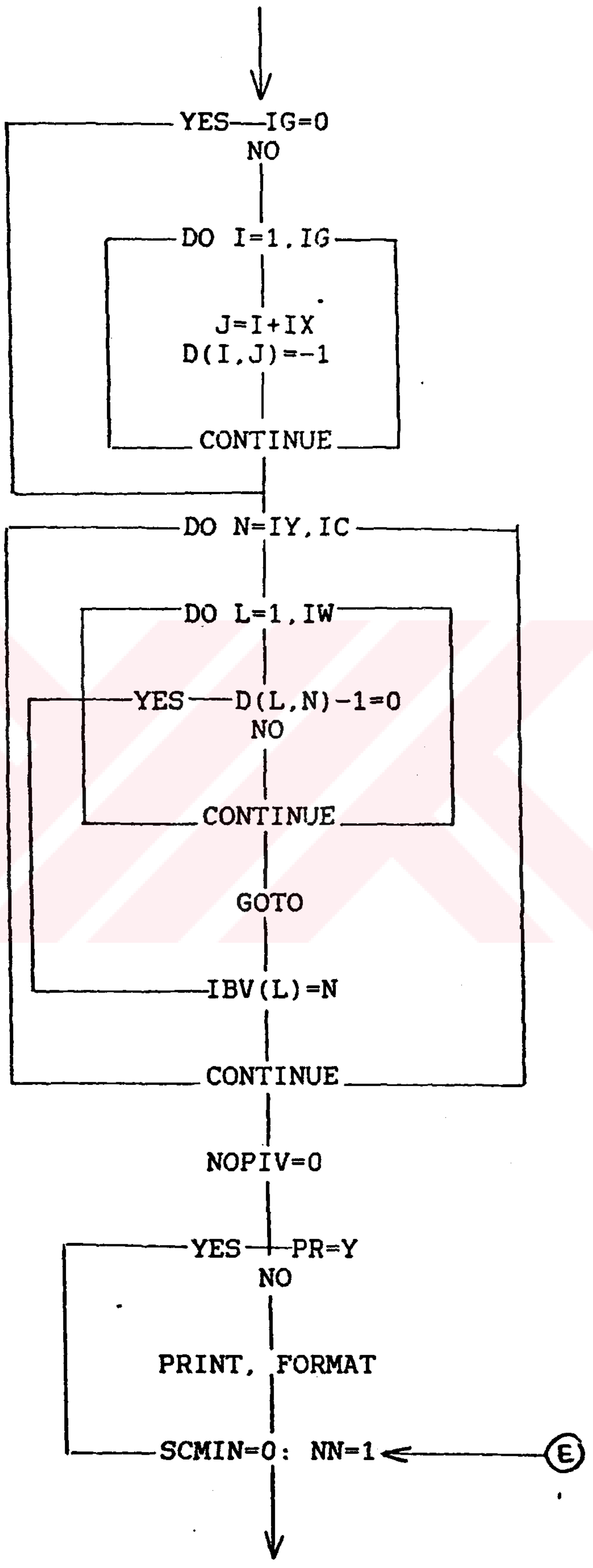
D.2. FLOW CHART

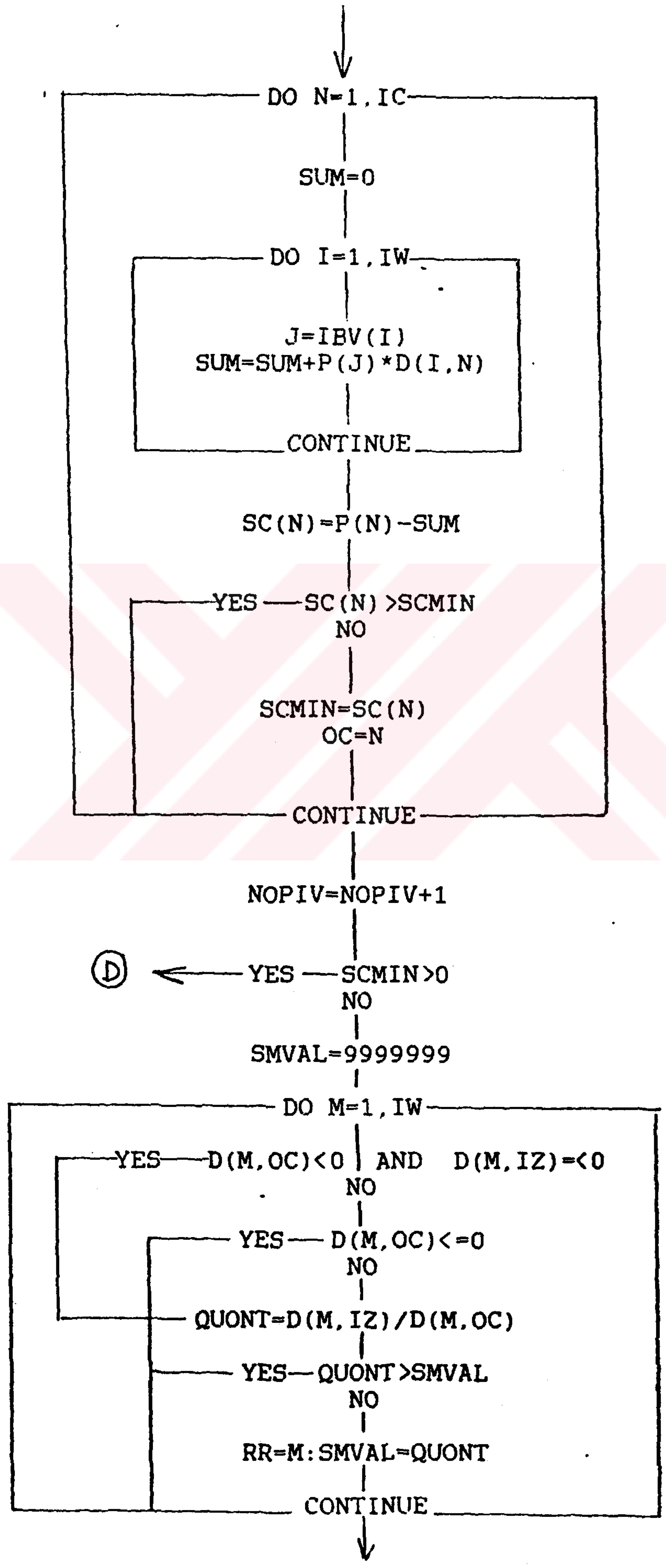


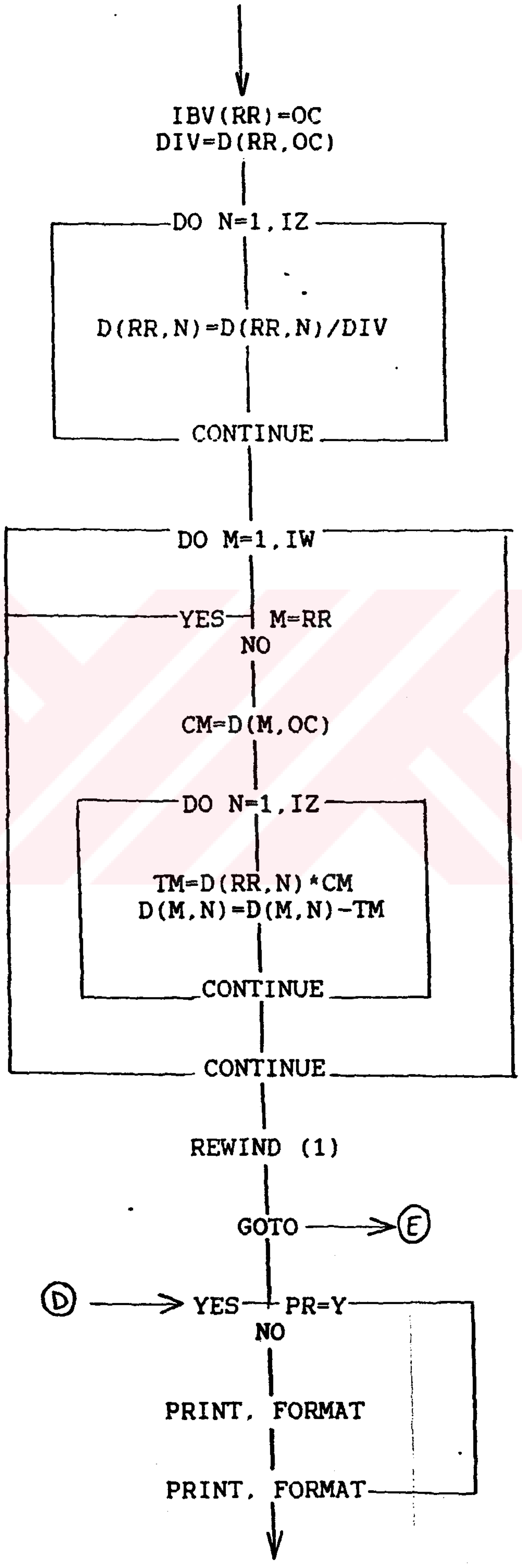

GOTO
B
INPUT H
NEW CS1,CLS
FOR NEW H
CS Sec 8.10
NRF Sec 8.10
CLF Sec 8.10
CF Sec 8.10
CFS Sec 8.10
A
SELECT DISPLAY TYPE
OF RESULTS ON SCREEN
(-ONLY RTC AND CS TABLE
-MIX TABLE
-OPTIMUM SOLUTION)
IZ=IX+IL+2*IG+NEQ+1
IC=IZ-1:IY=IX+1
DO 9000 IQ=1,9
DO 8000 MM=1,6
DO 3330 IJ=1,9
RTMX=9999999
DO 320 KK=1,6
DEFAULT P
(100,0.358,7.267,4.748,4.748)

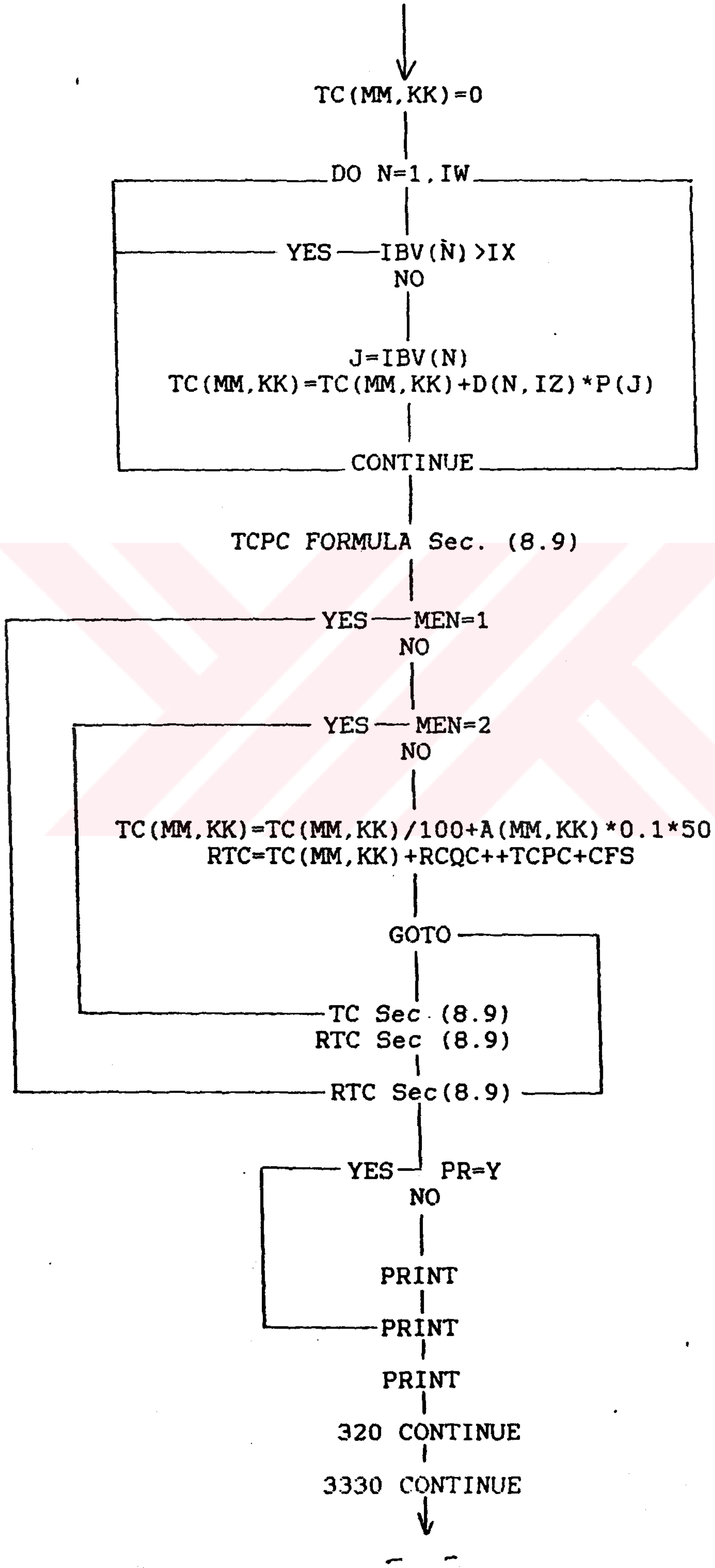

DO M=1,IW
DO N=1,IX
READ D(M,N)
CONTINUE
READ D(M,IZ)
CONTINUE
NN=0:G=IG+IY:F=G+IG+NEQ-1
GOSUB STANDEV
MEN=3
YES
NO
RSP=IJ/100
DEFAULT WATER REDUCTION
FORMULA CONSTANTS Tab. (7.1)
AIR CONTENT FORMULA
Eq. (7.6)
FCKF=FCK+1.28*SD
©
YES
MEN=1
NO
©
YES
MEN=3
NO
WR FORMULA Eq. (7.1)


CORRECTING THE WORKABILITY CONSTRAINS COEFF. ACCORDING TO WATER REDUCTION
C
CORRECTING THE STRENGTH AND VOLUME COEFF. ACCORDING TO CALCULATED AIR
DO I=IY,IC
P(I)=0
CONTINUE
IK=IG+NEQ
YES
IK=0
NO
DO K=G,F
P(K)=999
CONTINUE
DO I=1,IW
DO J=IY,IC
D(I,J)=0
CONTINUE
DO I=1,IW
J=I+IG+IX
D(I,J)=1
CONTINUE


YES
IG=0
NO
DO I=1,IG
J=I+IX
D(I,J)=-1
CONTINUE
DO N=IY,IC
DO L=1,IW
YES
D(L,N)-1=0
NO
CONTINUE
GOTO
IBV(L)=N
CONTINUE
NOPIV=0
YES
PR=Y
NO
PRINT, FORMAT
SCMIN=0: NN=1
E


DO N=1,IC
SUM=0
DO I=1,IW
J=IBV(I)
SUM=SUM+P(J)*D(I,N)
CONTINUE
SC(N)=P(N)-SUM
YES
SC(N)>SCMIN
NO
SCMIN=SC(N)
OC=N
CONTINUE
NOPIV=NOPIV+1
Ⓓ
YES
SCMIN>0
NO
SMVAL=9999999
DO M=1,IW
YES
D(M,OC)<0 AND D(M,IZ)=<0
NO
YES
D(M,OC)<=0
NO
QUONT=D(M,IZ)/D(M,OC)
YES
QUONT>SMVAL
NO
RR=M:SMVAL=QUONT
CONTINUE


IBV(RR)=OC
DIV=D(RR,OC)
DO N=1,IZ
D(RR,N)=D(RR,N)/DIV
CONTINUE
DO M=1,IW
YES
M=RR
NO
CM=D(M,OC)
DO N=1,IZ
TM=D(RR,N)*CM
D(M,N)=D(M,N)-TM
CONTINUE
CONTINUE
REWIND (1)
GOTO
E
D
YES
PR=Y
NO
PRINT, FORMAT
PRINT, FORMAT


TC(MM,KK)=0
DO N=1,IW
YES
IBV(N)>IX
NO
J=IBV(N)
TC(MM,KK)=TC(MM,KK)+D(N,IZ)*P(J)
CONTINUE
TCPC FORMULA Sec. (8.9)
YES
MEN=1
NO
YES
MEN=2
NO
TC(MM,KK)=TC(MM,KK)/100+A(MM,KK)*0.1*50
RTC=TC(MM,KK)+RCQC++TCPC+CFS
GOTO
TC Sec (8.9)
RTC Sec (8.9)
RTC Sec(8.9)
YES
PR=Y
NO
PRINT
PRINT
PRINT
320 CONTINUE
3330 CONTINUE

```
8000 CONTINUE
9000 CONTINUE
```

D.3. LIST OF COMPUTER PROGRAMME

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%%%%%%%%%%%%%%%     THIS PROGRAM IS A LINEAR OPTMIZATION     %%%%%%%
C%%%%%%%%%%%%%%%          PROGRAM IN FORTRAN 77               %%%%%%%
C%%%%%%%%%%%%%%%     FOR OPTIMUM MIX DESIGN OF READY MIXED    %%%%%%%
C%%%%%%%%%%%%%%%  CONCRETE AS A FUNCTION OF SUPERPLASTICIZER  %%%%%%%
C%%%%%%%%%%%%%%%      CONTENT AND CONTROL STANDARD            %%%%%%%
C%%%%%%%%%%%%%%%                                              %%%%%%%
C%%%%%%%%%%%%%%%                  by                          %%%%%%%
C%%%%%%%%%%%%%%%             Ihsan GUVEN                      %%%%%%%
C%%%%%%%%%%%%%%%             Nildem TAYSI                     %%%%%%%
C%%%%%%%%%%%%%%%                                              %%%%%%%
C%%%%%%%%%%%%%%%                                              %%%%%%%
C%%%%%%%%%%%%%%%       Developed and Adapted by               %%%%%%%
C%%%%%%%%%%%%%%%          Ergin Oral DEMIREL                  %%%%%%%
C%%%%%%%%%%%%%%%                                              %%%%%%%
C%%%%%%%%%%%%%%%             Supervised by                    %%%%%%%
C%%%%%%%%%%%%%%%           ABDURRAHMAN GUNER                  %%%%%%%
C%%%%%%%%%%%%%%%                                              %%%%%%%
C%%%%%%%%%%%%%%%               JUNE,1994                      %%%%%%%
C%%%%%%%%%%%%%%%               GAZIANTEP                      %%%%%%%
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        INTEGER FCK(6),SL
        DIMENSION P(35),D(50,99),SC(99),IBV(50),SD(6,6),TC(6,6),
     *  RCQC(6),RTC(6,6),B(6,6),WC(6,6),A(6,6),SL(9),SP(9),ERG(6,9,9)
     *  CCP(6,9,9),ERC(6,9,9),ERW(6,9,9),ERAI(6,9,9),
     *  ERAJ(6,9,9),ERAK(6,9,9),AGG1(6,6),AGG2(6,6),AGG3(6,6),
     *  TOTAL(6,9,9),AIRP(6,9,9),AGGO(6,6),SPX(6,6),ERAL(6,9,9),
     *  ERAM(6,9,9)
        CHARACTER*3 PR/'YES'/
C       RCQC(I):Relative cost of quality control as
C               a function of control standard.
        DATA (RCQC(I),I=1,6)/45.2,33.6,24.9,14.7,2.4,0.5/
C       FCK(N):Characteristic strength (Concrete Class)
        DATA (FCK(N),N=1,6)/14,16,18,20,25,30/
        OPEN(1,File='DATA.FILE',Status='OLD')
        OPEN(6,File='OPTIM.DATA',Status='NEW')
        OPEN(7,File='RTCTAB.DATA',Status='NEW')
        OPEN(8,File='MIXTAB.DATA',Status='NEW')
        WRITE(*,'(''1'')')
C       IW:Number of constraints.
        IW=15
C       IL:Number of less thans.
        IL=0
C       IG:Number of greater thans.
        IG=13
C       NEQ:Number of equalities.
        NEQ=2
C       IX:Number of real variables
        IX=6
        PRINT*,'    '
        PRINT*,'    '
        PRINT 12
```

```
12        FORMAT(23X,8HMENU (1))
          PRINT 11
11        FORMAT(18X,'------------------------------')
          PRINT 13
13        FORMAT(23X,9HADMIXTURE)
          PRINT 14




14        FORMAT(18X,'------------------------------')
          PRINT 15
15        FORMAT(20X,' NONE                    (1)')
          PRINT 16
16        FORMAT(20X,' SP% SUPERPLASTICIZER    (2)')
          PRINT 17
17        FORMAT(20X,' 10% C.SILICA FUME      (3)')
          PRINT 18
18        FORMAT(18X,'------------------------------')
          PRINT*,'   '
          PRINT*,'   '
          PRINT 19
19        FORMAT(18X,'WHICH ONE IS YOUR SELECTION ? ',$,10(/))
          READ*,MEN
          PRINT*,'   '
          PRINT*,'   '
          PRINT*,'   '
          PRINT*,'   '
          PRINT*,'   '
          PRINT*,'   '
          PRINT 700
700       FORMAT(23X,8HMENU (2))
          PRINT 701
701       FORMAT(18X,'------------------------------')
          PRINT 702
702       FORMAT(23X,17HSTRENGTH FUNCTION)
          PRINT 703
703       FORMAT(18X,'------------------------------')
          PRINT 704
704       FORMAT(20X,' GRAFF                    (1)')
          PRINT 705
705       FORMAT(20X,' MODIFIED GRAFF           (2)')
          PRINT 706
706       FORMAT(20X,' FERET                   (3)')
          PRINT 707
707       FORMAT(18X,'------------------------------')
          PRINT*,'   '
          PRINT*,'   '
          PRINT 708
708       FORMAT(18X,'WHICH ONE IS YOUR SELECTION ? ',$,5(/))
          READ*,MEN2
C         SL:Slump in mm.
          DATA (SL(IQ),IQ=1,9)/50,60,80,100,125,150,175,200,225/
          DO 934 IQ=1,9
          PRINT 935,IQ,SL(IQ)
935       FORMAT(29X,'SL(',I1,')=',1X,I3,'mm',/)
934       CONTINUE
933       PRINT 936
936       FORMAT(22X,'PRESS ENTER TO CONTINUE',3(/))
          READ(*,*,END=933,ERR=933)
C         SP:Percentage of Superplasticizer content.
          DATA (SP(IJ),IJ=1,9)/0,0.25,0.5,0.75,1,1.25.1.5,1.75.2/
          DO 937 IJ=1,9
          PRINT 938,IJ,SP(IJ)
```

```
938       FORMAT(29X,'SP(',I1,')=',1X,F4.2,'%',/)
937       CONTINUE
940       PRINT 939
939       FORMAT(22X,'PRESS ENTER TO CONTINUE',5(/))
          READ(*,*,END=940,ERR=940)
          PRINT 3




3         FORMAT(1H1,18X,'DO YOU WANT TO ADD CFS INTO OPTIMIZATION? (Y/N)
     *  13(/))
          READ(5,2) FS
2         FORMAT(A1)
          IF(FS.EQ.'Y') GOTO 248
          CFS=0
          GOTO 238
C        AF:Amount of formwork in meter square per cubic meter of concrete
C        CF:Cost of formwork per cubic meter of concrete
C        CF1:Cost of formwork per meter square
248       CF1=13.5325*SL(IQ)**2-4736.37*SL(IQ)+453282.27
          AF=7
          CC=750
          NRS=15
C        CS:Relative cost of scaffolding was not taken account as an
C           optimazation variable but it is included in the relative cost
C           as a function of the story height of the building
C         H:Story height
C       CS1:Cost of scaffolding per cubic meter
C       CLS:Cost of lumber of scaffolding

          PRINT 405
405       FORMAT(1H1,18X,'DO YOU WANT TO SPECIFY H HIGHER THAN 4M? (Y/N)'
     *  10(/))
          READ (5,9) PP
9         FORMAT(A1)
877       IF(PP.EQ.'Y') GO TO 420
          CS1=17036
          CLS=9960
          H=4
          GO TO 520
420       PRINT 23
23        FORMAT(18X,3H H=)
          READ (5,6)H
6         FORMAT(F5.2)
          IF(H.LE.6)GO TO 440
          GO TO 450
440       CS1=34697
          CLS=18260
          GO TO 520
450       IF(H.LE.8)GO TO 460
          GO TO 470
460       CS1=42103
          CLS=20760
          GO TO 520
470       IF(H.LE.10)GO TO 480
          GO TO 490
480       CS1=69644
          CLS=30710
          GO TO 520
490       CS1=86618
          CLS=33200
          GOTO 520
C       CFS:Relative cost of formwork and scaffolding kg cement per cubic
```

```
C--------concrete-------------------------------------------
520     CS=CS1-CLS*(1-1/NRS)
        NRF=0.00121*SL(IQ)**2-0.4235*SL(IQ)+45.05
        CLF=6.59*SL(IQ)**2-2306.12*SL(IQ)+222543.2
        CF=CF1-CLF*(1-1/NRF)
        CFS=(CF+CS*H)*AF/CC




238     WRITE(*,'(''1'')')
        PRINT 1021
1021    FORMAT(1H1,15X,'DO YOU WANT TO SEE ONLY
     *RTC AND CS TABLE ? (Y/N)',10(/)) .
        READ(5,5) RTCT
        PR='Y'
        IF(RTCT.EQ.'Y') GOTO 878
        AB=0
        PRINT 6010
6010    FORMAT(1H1,15X,'DO YOU WANT TO SEE ONLY
     *MIX TABLE ? (Y/N)',10(/))
        READ(5,5) MIT
        IF(MIT.EQ.'N') AB=1
        IF(MIT.EQ.'Y') GOTO 878
        PRINT 21
21      FORMAT(1H1,15X,'DO YOU WANT TO SEE ONLY
     * OPTIMUM SOLUTION ? (Y/N)',10(/))
        READ(5,5) PR
5       FORMAT(A1)
878     IZ=IX+IL+2*IG+NEQ+1
        IC=IZ-1
        IY=IX+1
        DO 9000 IQ=1,9
        DO 8000 MM=1,6
        DO 3330 IJ=1,9
        RTMX=99999999
        DO 320 KK=1,6
        DATA (P(N),N=1,6)/100,.358,16.267,4.748,4.748.1500/
        DO 500 M=1,IW
        DO 600 N=1,IX
        READ(1,*),D(M,N)
600     CONTINUE
        READ(1,*),D(M,IZ)
500     CONTINUE
        WRITE(*,'(''1'')')
        NN=0
        PRINT*,'    '
        G=IG+IY
        F=G+IG+NEQ-1
        CALL STANDEV(SD,MM,KK)
        IF(MEN.EQ.3) GO TO 40
C       SD(MM,KK):Standard  deviations for each FCK and
C       Control Standard.
        RSP=SP(IJ)/100
        IF(FCK(MM).EQ.14) GOTO 7007
        GOTO 7008
7007    WCR=0.58
        RI=.215
        MO=80.9
        GOTO 7006
7008    IF(FCK(MM).EQ.16) GOTO 7010
        GOTO 7009
7010    WCR=.54
        RI=.279
```

```
        MO=60.6
        GOTO 7006
7009    IF(FCK(MM).EQ.20) GOTO 7011
        GOTO 7012
7011    WCR=.45
        RI=.379
```

```
        MO=110.4
        GOTO 7006
7012    IF(FCK(MM).EQ.25) GOTO 7013
        GOTO 7014
7013    WCR=.4
        RI=.284
        MO=80.4
        GOTO 7006
7014    IF(FCK(MM).EQ.30) GOTO 7015
        GOTO 7016
7015    WCR=.38
        RI=.278
        MO=105
        GOTO 7006
7016    IF(FCK(MM).EQ.35) GOTO 7017
        GOTO 7006
7017    WCR=.35
        RI=.278
        MO=105
7006    VA=(6.0358*WCR-8.9982*WCR**2+230.848*RSP-1687.06*RSP**2)*10

        D(15,1)=RSP
        FCKF=FCK(MM)+1.28*SD(MM,KK)
6007    IF(MEN2.EQ.1) GOTO 720
        IF(MEN2.EQ.2) GOTO 730
        CF=145.451+3687.097*RSP-107223*RSP**2
732     D(2,1)=((1-(FCKF/CF)**.5)/2996)*1000
        D(2,2)=-((((FCKF/CF)**.5))/999.43)*1000
        AV=VA
        CA=CF
        GOTO 50
720     CG=7.2816-204.052*RSP+17464.28*RSP**2
        D(2,2)=-(FCKF*CG/37.2)**.5
        AV=VA
        FCKF=0
        CA=37.2/CG
        GOTO 50
730     CGM=6.860907-350.174*RSP+10853.35*RSP**2
        D(2,2)=-(FCKF*CGM/37.2)**.5
        AV=VA
        CA=37.2/CGM
        GOTO 50
40      D(2,2)=(-1)*((FCK(MM)+1.28*SD(MM,KK))/5.045045)**(.25)
50      IF(MEN.EQ.1) GO TO 147
        IF(MEN.EQ.3) GO TO 147
C       Wr: Water Reduction Factor
        Wr=RI*(1-2.718281828**(-RSP*MO))
        D(6,1)=D(6,1)*(1-Wr)
        D(6,3)=D(6,3)*(1-Wr)
        D(6,4)=D(6,4)*(1-Wr)
        D(6,5)=D(6,5)*(1-Wr)
        D(6,6)=D(6,6)*(1-Wr)
147     D(6,IZ)=(82.59+1.015*SL(IQ)-.00608*SL(IQ)**2 ,
      * +.0000137*SL(IQ)**3)*(1-Wr)
```

```
10001   D(Z,IZ)=(VA/1000)*(FCKF/CA)**.5
        D(14,IZ)=1000-AV
        DO 1000 I=IY,IC
        P(I)=0
1000    CONTINUE
        IK=IG+NEQ




        IF(IK.EQ.0) GOTO 60
        DO 1100 K=G,F
        P(K)=999
1100    CONTINUE
60      DO 1200 I=1,IW
        DO 1200 J=IY,IC
        D(I,J)=0
1200    CONTINUE
        DO 1400 I=1,IW
        J=I+IG+IX
        D(I,J)=1
1400    CONTINUE
        IF(IG.EQ.0) GO TO 70
        DO 1500 I=1,IG
        J=I+IX
        D(I,J)=-1
1500    CONTINUE
70      DO 1600 N=IY,IC
        DO 1700 L=1,IW
        IF(D(L,N)-1.EQ.0) GOTO 80
1700    CONTINUE
        GOTO 1600
80      IBV(L)=N
1600    CONTINUE
        NOPIV=0
        IF(PR.EQ.'Y') GOTO 110
C*************************************************
        WRITE(*,'(''1'')')
        PRINT 133
133     FORMAT(18X,'INITIAL SIMPLEX TABLEAU')
        PRINT 134
134     FORMAT(18X,'________________________')
        PRINT*,'    '
        GO TO 120
C*************************************************
110     SCMIN=0
        NN=1
        DO 1800 N=1,IC
        SUM=0.0
        DO 1900 I=1,IW
        J=IBV(I)
        SUM=SUM+P(J)*D(I,N)
1900    CONTINUE
        SC(N)=P(N)-SUM
        IF(SC(N).GT.SCMIN) GOTO 1800
        SCMIN=SC(N)
        OC=N
1800    CONTINUE
        NOPIV=NOPIV+1
        IF(SCMIN.GE.0) GOTO 120
        SMVAL=9999999.
        DO 2000 M=1,IW
        IF(D(M,OC).LT.0.AND.D(M,IZ).LT.0) GO TO 140
        IF(D(M,OC).LE.0) GOTO 2000
```

```
140        QUONT=D(M,IZ)/D(M,OC)
           IF(QUONT.GT.SMVAL) GOTO 2000
           RR=M
           SMVAL=QUONT
2000       CONTINUE
           IBV(RR)=OC




           DIV=D(RR,OC)
           DO 2100 N=1,IZ
           D(RR,N)=D(RR,N)/DIV
2100       CONTINUE
           DO 2200 M=1,IW
           IF(M.EQ.RR) GOTO 2200
           CM=D(M,OC)
           DO 2300 N=1,IZ
           TM=D(RR,N)*CM
           D(M,N)=D(M,N)-TM
2300       CONTINUE
2200       CONTINUE
           REWIND(1)
           GOTO 110
120        IF(PR.EQ.'Y') GO TO 170
C***********************************************
           PRINT 115,(P(N),N=1,IC)
 115       FORMAT(1X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3
      *,4X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3,4X,F7.3)
           PRINT 116
116        FORMAT(2X,'--------------------------------------------------
      *------------------------------------------------------------
      *------------')
           PRINT 117
117        FORMAT(6X,'X1',8X,'X2',8X,'X3',8X,'X4',8X,'X5',8X,'X6',8X
      *,'X7',8X,'X8',8X,'X9',7X,'X10',7X,'X11',7X,'X12',7X,'X13')
           PRINT 118
118        FORMAT(2X,'--------------------------------------------------
      *------------------------------------------------------------
      *------------')
           DO 2600 M=1,IW
           PRINT 119,(D(M,N),N=1,IZ)
119        FORMAT(F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X
      *,F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X,F9.3,1X,F9.3)
           PRINT*,'    '
2600       CONTINUE
           PRINT*,'    '
           IF(NN.EQ.0) GO TO 110
C***********************************************
170        IF(PR.EQ.'Y') GO TO 180
           PRINT 121,(SC(N),N=1,IC)
121        FORMAT(F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3
      *,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3)
           PRINT*,'    '
           PRINT 104,NOPIV
104        FORMAT(8X,'OPTIMIZED QUANTITIES ARE FOUND AFTER',2X,I2,2X
      *,'ITERATIONS',//)
190        PRINT 105
105        FORMAT(22X,'PRESS ENTER TO CONTINUE')
           READ(*,*,END=190,ERR=190)
           WRITE(*,'(''1'')')
           PRINT 122,KK,FCK(MM),SD(MM,KK),RCQC(KK),SL(IQ),SP(IJ)
122        FORMAT(4X,'CS=',I1,3X,'FCK=',I2,3X,'SD=',F8.3,3X
      *,'RCQC=',F4.1,3X,'=',I3,'mm'3X,'SP=',F4.2,'%')
           PRINT*,'    '
```

```
        PRINT*,'
        PRINT*,'   '
        PRINT 109
109     FORMAT(8X,8HVARIABLE,6X,8HQUANTITY,6X,5HPRICE)
        PRINT 101
101     FORMAT(8X,8H________,6X,8H________,6X,5H_____)




C***********************************************
180     TC(MM,KK)=0
        DO 2900 N=1,IW
        IF(IBV(N).GT.IX) GO TO 2900
        J=IBV(N)
        IF(PR.EQ.'Y') GOTO 220
        PRINT 124,IBV(N),D(N,IZ),P(J)
124     FORMAT(11X,'X',I2,7X,F9.3,5X,F7.3)
220     TC(MM,KK)=TC(MM,KK)+D(N,IZ)*P(J)
        IF(J.EQ.1) A(MM,KK)=D(N,IZ)
        IF(J.EQ.2) B(MM,KK)=D(N,IZ)
        IF(J.EQ.3) AGG1(MM,KK)=D(N,IZ)
        IF(J.EQ.4) AGG2(MM,KK)=D(N,IZ)
        IF(J.EQ.5) AGG3(MM,KK)=D(N,IZ)
        IF(J.EQ.6) SPX(MM,KK)=D(N,IZ)
2900    CONTINUE
C TCPC:Total cost of  placing and compacting for C30.
        TCPC=9.818+1.8883*EXP(-0.01946*SL(IQ))
        IF(MEN.EQ.1) GOTO 230
        IF(MEN.EQ.2) GOTO 240
        TC(MM,KK)=TC(MM,KK)/100+A(MM,KK)*.1*50
C       RTC(MM,KK):Relative total cost.
        RTC(MM,KK)=TC(MM,KK)+RCQC(KK)+TCPC+CFS
        GOTO 250
240     TC(MM,KK)=TC(MM,KK)/100+(A(MM,KK)*(SP(IJ)/100)*15)
        RTC(MM,KK)=TC(MM,KK)+RCQC(KK)+TCPC+CFS
        GOTO 250
230     RTC(MM,KK)=TC(MM,KK)/100+RCQC(KK)+TCPC+CFS
250     WC(MM,KK)=B(MM,KK)/A(MM,KK)
        IF(PR.EQ.'Y') GOTO 260
C***********************************************
        PRINT*,'   '
        PRINT*,'   '
        PRINT 135
135     FORMAT(8X,'TOTAL COST',6X,'   RTC')
        PRINT 136
136     FORMAT(8X'__________',6X,'__________')
        PRINT 137,TC(MM,KK),RTC(MM,KK)
137     FORMAT(6X,F10.3,6X,F10.3)
        PRINT*,'   '
        PRINT*,'   '
270     PRINT 138
138     FORMAT(22X,'PRESS ENTER TO CONTINUE')
        READ(*,*,END=270,ERR=270)
C***********************************************
        IF(PR.EQ.'Y') GOTO 260
        GOTO 320
260     CONTINUE
        IF (RTMX.LT.RTC(MM,KK)) GOTO 888
        RTMX=RTC(MM,KK)
        KKMX=KK
        CCP(MM,IQ,IJ)=KKMX
        SDMX=SD(MM,KK)
        AMX=A(MM,KK)
```

```
      AGG1X=AGG1(MM,KK)
      AGG2X=AGG2(MM,KK)
      AGG3X=AGG3(MM,KK)
      WCMX=WC(MM,KK)
      TCMX=TC(MM,KK)
      TCPCMX=TCPC




      WMX=WCMX*AMX
      ERG(MM,IQ,IJ)=RTMX
      ERC(MM,IQ,IJ)=A(MM,KK)
      ERW(MM,IQ,IJ)=B(MM,KK)
      AGGOX=AGGO(MM,KK)
      XSPX=SPX(MM,KK)
      AX1=D(IBV(3),IZ)
      AX2=D(IBV(6),IZ)
      ERAI(MM,IQ,IJ)=AGG1X
      ERAJ(MM,IQ,IJ)=AGG2X
      ERAL(MM,IQ,IJ)=AGGOX
      IF(AX2.GT.10) GOTO 721
      AX3=D(IBV(6),IZ)
      ERAK(MM,IQ,IJ)=AGG3X
      ERAL(MM,IQ,IJ)=AGGOX
      ERAM(MM,IQ,IJ)=XSPX
      GOTO 888
721   AX3=D(IBV(5),IZ)
      ERAL(MM,IQ,IJ)=AGGOX
      ERAK(MM,IQ,IJ)=AGG3X
      ERAM(MM,IQ,IJ)=XSPX
888   IF(KK.EQ.6) GOTO 995
      IF(KK.LT.6) GOTO 320
995   IF(RTCT.EQ.'Y') GOTO 801
      IF(AB.EQ.0) GOTO 320
      PRINT 331
331   FORMAT(25X,'OPTIMUM SOLUTION',/,24X,'====================',/)
      PRINT 102,SL(IQ),SP(IJ),KKMX,FCK(MM),SDMX
102   FORMAT(16X,'SLUMP=',1X,I3,'mm',8X,'SP=',1X,F4.2,'%',/
     *,16X,'-------------------------------',/,/,/
     *,16X,'CS=',1X,I1,6X'FCK=',1X,I2,6X,'SD=',1X,F6.3,/,16X,'---
     *-------------------------------',/,/)
      PRINT 103,AMX,WMX,AX1,AX2,AX3,WCMX,TCMX,TCPCMX,RTMX
103   FORMAT(4X,'C=',F5.0,4X,'W=',F5.0,4X,'A1=',F6.0,4X,'A2=',F5.0,4X,
     *'A3=',F6.0,/,/,16X,'W/C=',F6.4,/,16X,
     *'RTCM='F9.2,8X,'TCPC='F5.2,4(/),30X,'RTC=',1X,F7.0,/,28X,'=====
     *=========',/,/)
1001  PRINT 4000
4000  FORMAT(22X,'PRESS ENTER TO CONTINUE')
      READ(*,*,END=1001,ERR=1001)
      PC=0
      GOTO 320
801   PRINT 802,SL(IQ),FCK(MM),SP(IJ)
802   FORMAT(15X,'SLUMP=',I3,8X,'FCK=',I2,8X,'SP(%)=',F5.2)
320   CONTINUE
3330  CONTINUE
      WRITE(*,'(''1'')')
      IF(PR.EQ.'Y') GOTO 330
      GOTO 340
330   WRITE(6,125)
125   FORMAT(4(/),11X,'OPTIMIZED MIX PROPORTIONS AND COSTS')
      IF(MEN.EQ.1) GOTO 370
      IF(MEN.EQ.2) GOTO 360
      WRITE(6,111)
111   FORMAT(11X,'IF 1% AND 10% BY WEIGHT OF CEMENT OF SUPERPLAS
```

```
111     FORMAT(11X,'IF 1% AND 10% BY WEIGHT OF CEMENT OF SUPERPLAS
     *TICISER',/,2X,'AND CONDENSED SILICA FUME,RESPECTIVELY,ARE
     *USED IN THE MIX')
        GO TO 350
370     WRITE(6,149)SL(IQ)
149     FORMAT(11X,'FOR 0.00% SUPERPLASTICISER AND',1X,I3



     *,1X,'mm. SLUMP')
        GO TO 350
360     WRITE(6,112)SP(IQ),SL(IQ)
112     FORMAT(11X,'FOR',1X,F5.2,1X,'% SUPERPLASTICISER AND',1X,I3
     *,1X,'mm. SLUMP')
350     WRITE(6,145)
145     FORMAT(11X,'-----------------------------------------------
     *-------------------------------')
        WRITE(6,146)
146     FORMAT(11X,'CONCRETE',1X,'CONTROL')
        WRITE(6,113)
113     FORMAT(11X,'CLASS',4X,'STANDARD',1X,'Excellent',2X,'Very Good
     *',2X,'Good',6X,'Poor',4X,'Very Poor',3X,'No Control')
        WRITE(6,114)
114     FORMAT(20X,'L',9X,'1',10X,'2',10X,'3',10X,'4',10X,'5',10X,'6')
        WRITE(6,108)
108     FORMAT(11X,'-----------------------------------------------
     *-------------------------------')
        DO 3000 M=1,6
        WRITE(6,131)FCK(M),(SD(M,K),K=1,6)
131     FORMAT(11X,'C',I2,6X,'SD',7X,F5.2,6X,F5.2,6X,F5.2,6X,F5.2,6X
     *,F5.2,6X,F5.2)
        WRITE(6,128) (RTC(M,K),K=1,6)
128     FORMAT(20X,'RTC',6X,F5.0,6X,F5.0,6X,F5.0,6X,F5.0,6X,F5.0,6X
     *,F5.0)
        WRITE(6,129)(A(M,K),K=1,6)
129     FORMAT(20X,'C',8X,F5.0,6X,F5.0,6X,F5.0,6X,F5.0,6X,F5.0,6X
     *,F5.0)
        WRITE(6,106) (WC(M,Y),Y=1,6)
106     FORMAT(20X,'W/C',7X,F6.4,5X,F6.4,5X,F6.4,5X,F6.4,5X,F6.4,5X
     *,F6.4)
        WRITE(6,130)
130     FORMAT(11X,'-----------------------------------------------
     *-------------------------------')
        CP=0
3000    CONTINUE
        IF(RTCT.EQ.'Y') GOTO 8000
        PRINT *,'    '
        PRINT *,'    '
        PRINT *,'    '
        PRINT *,'    '
5000    PRINT 742,FCK(MM),SL(IQ)
742     FORMAT(30X,'FCK=',I2,4X,'SL=',I3,'mm')
        PRINT *,'    '
        PRINT *,'    '
        PRINT *,'    '
        PRINT 739
739     FORMAT(6X,'SP%',4X,'RTC -CS',4X,'C,Kg',4X,'W,Kg',5X,'A1,Kg',
      * 3X,'A2,Kg',4X,'A3,Kg',3X,'AIR %',2X,'SP,Kg')
        PRINT 740
740     FORMAT(5X,'=====',3X,'========',3X,'=====',3X,'=====',
      * 4X,'=====',3X,'=====',4X,'=====',3X,'====',3X,'=====')
        DO 736 IJ=1,9
        TOTAL(MM,IQ,IJ)=ERC(MM,IQ,IJ)+ERW(MM,IQ,IJ)+ERAI(MM,IQ,IJ)+
```

```
     * ERAJ(MM,IQ,IJ)+ERAK(MM,IQ,IJ)+ERAL(MM,IQ,IJ)+ERAM(MM,IQ,IJ)
        AIRP(MM,IQ,IJ)=(1-(ERC(MM,IQ,IJ)/2996)-
     * (ERW(MM,IQ,IJ)/999.43)-(ERAI(MM,IQ,IJ)/2716.5)-
     * (ERAJ(MM,IQ,IJ)/2714.1)-(ERAK(MM,IQ,IJ)/2697.8)-
     * ((ERC(MM,IQ,IJ)*SP(IJ)/100)/1198))*100
        PRINT 735,SP(IJ),ERG(MM,IQ,IJ),CCP(MM,IQ,IJ),




     * ERC(MM,IQ,IJ),ERW(MM,IQ,IJ),ERAI(MM,IQ,IJ),ERAJ(MM,IQ,IJ),
     * ERAK(MM,IQ,IJ),AIRP(MM,IQ,IJ),ERAM(MM,IQ,IJ)
735     FORMAT(4X,F5.2,'%',3X,F5.0,'-',F2.0,4X,F5.0,3X,F4.0,4X,F6.0,
     * 3X,F5.0,3X,F6.0,1X,F6.2,3X,F6.2)
736     CONTINUE
        PRINT *,'    '
        PRINT *,'    '
737     PRINT 738
738     FORMAT(22X,'PRESS ENTER TO CONTINUE')
        READ(*,*,END=737,ERR=737)
8000    CONTINUE
9000    CONTINUE
        CLOSE(1)
        DO 6005 MM=1,6
        DO 6005 IQ=1,9
        PRINT *,'     '
        WRITE (8,6000) FCK(MM),SL(IQ)
6000    FORMAT(/,30X,'FCK=',I2,4X,'SL=',I3,'mm')
        WRITE (8,6001)
6001    FORMAT(15X,'SP%',3X,'RTC',4X, 'CS',3X,'W,kg',2X,'SP,kg',
     * 3X,'C,kg',3X,'A1,kg',2X,'A2,kg',3X,'A3,kg',2X,'AIR %',1X,'SP,Kg')
        WRITE (8,6002)
6002    FORMAT(14X,'=====',2X,'=====',2X,'==',2X,'=====',2X,'=====',
     * 2X,'=====',3X,'=====',2X,'=====',3X,'=====',2X'====',2X,'=====')
        DO 6004 IJ=1,9
        SPQ=SP(IJ)*ERC(MM,IQ,IJ)/100
        TOTAL(MM,IQ,IJ)=ERC(MM,IQ,IJ)+ERW(MM,IQ,IJ)+ERAI(MM,IQ,IJ)+
     * ERAJ(MM,IQ,IJ)+ERAK(MM,IQ,IJ)+ERAL(MM,IQ,IJ)+ERAM(MM,IQ,IJ)
        AIRP(MM,IQ,IJ)=(1-(ERC(MM,IQ,IJ)/2996)-
     * (ERW(MM,IQ,IJ)/999.43)-(ERAI(MM,IQ,IJ)/2716.5)-
     * (ERAJ(MM,IQ,IJ)/2714.1)-(ERAK(MM,IQ,IJ)/2697.8)-
     * ((ERC(MM,IQ,IJ)*SP(IJ)/100)/1198))*100
        WRITE(8,6003) SP(IJ),ERG(MM,IQ,IJ),CCP(MM,IQ,IJ),
     * ERW(MM,IQ,IJ),SPQ,ERC(MM,IQ,IJ),ERAI(MM,IQ,IJ),ERAJ(MM,IQ,IJ),
     * ERAK(MM,IQ,IJ),AIRP(MM,IQ,IJ),ERAM(MM,IQ,IJ)
6003    FORMAT(13X,F5.2,'%',2X,F5.0,2X,F3.0,3X,F4.0,2X,F4.1,3X,
     * F4.0,2X,F6.0,2X,F5.0,2X,F6.0,2X,F4.1,2X,F6.2)
6004    CONTINUE
6005    CONTINUE
751     WRITE(7,744) SL(1),SL(2),SL(3),SL(4),SL(5),SL(6),SL(7),
     * SL(8),SL(9)
744     FORMAT(9X,I3,8X,I3,8X,I3,8X,I3,8X,I3,8X,I3,8X,I3,8X,I3,8X,I3)
        DO 745 MM=1,6
        WRITE(7,748) FCK(MM)
748     FORMAT(/,1X,'FCK=',I2)
        DO 757 IJ=1,9
        WRITE(7,752) SP(IJ),ERG(MM,1,IJ),CCP(MM,1,IJ),
     * ERG(MM,2,IJ),CCP(MM,2,IJ),ERG(MM,3,IJ),CCP(MM,3,IJ),
     * ERG(MM,4,IJ),CCP(MM,4,IJ),ERG(MM,5,IJ),CCP(MM,5.IJ),
     * ERG(MM,6,IJ),CCP(MM,6,IJ),ERG(MM,7,IJ),CCP(MM,7,IJ),
     * ERG(MM,8,IJ),CCP(MM,8,IJ),ERG(MM,9,IJ),CCP(MM,9.IJ)
752     FORMAT(2X,F4.2,'%',4X,F6.0,1X,F2.0,4X,F6.0,1X,F2.0,
     * 4X,F6.0,1X,F2.0,4X,F6.0,1X,F2.0,4X,F6.0,1X,F2.0,
     * 4X,F6.0,1X,F2.0,4X,F6.0,1X,F2.0,4X,F6.0,1X,F2.0,
     * 4X,F6.0,1X,F2.0)
```

```
757      CONTINUE
745      CONTINUE
340      STOP
         END
         SUBROUTINE STANDEV(SD,MM,KK)




         INTEGER FCK(6),FCKO
         REAL M,SD(6,6)
         DATA (FCK(I),I=1,6)/14,16,18,20,25,30/,FCKO/25/
C      Z Score was taken as 1.28 for 90 % level of confidence according
C        to related Turkish standard,TS 500
         Z=1.28
         M=0.00054348
         DO 10 I=1,MM
         IF (FCK(I).LT.FCKO) THEN
         S=0.0
         ELSE IF (FCK(I).GT.FCKO) THEN
         S=1.0
         ENDIF
         DO 10 J=1,KK
         FCS=0.0775+0.0225*J
         VM=FCS*(1.-S*(M/FCS)*(FCK(I)-FCKO))
         SD(I,J)=(VM*FCK(I))/(1.-Z*VM)
 10      CONTINUE
         RETURN
         END
```

D.4. OPTIMUM MIX PROPORTIONS(TO BE USED IN CONJUCTION WITH TABLE 8.6.8, p 194)

FCK=14 SL= 50mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	509.	5.	191.	0.0	318.	756.	554.	582.	0.4	0.00
0.25%	525.	5.	197.	0.8	313.	745.	546.	573.	1.0	0.78
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	558.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	650.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL= 60mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	508.	5.	191.	0.0	318.	756.	555.	582.	0.4	5.90
0.25%	525.	5.	197.	0.8	313.	745.	546.	573.	1.0	0.78
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	558.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	650.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL= 80mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	510.	5.	200.	0.0	332.	666.	617.	576.	0.4	5.90
0.25%	524.	5.	197.	0.8	313.	745.	546.	573.	1.0	0.78
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	558.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=100mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	513.	5.	206.	0.0	342.	620.	644.	571.	0.3	5.90
0.25%	524.	5.	197.	0.8	313.	745.	546.	573.	1.0	0.78
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	558.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=125mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	518.	5.	210.	0.0	350.	599.	648.	568.	0.3	5.90
0.25%	525.	5.	199.	0.8	317.	721.	562.	571.	1.0	0.79
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55

0.75%	558.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=150mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	521.	5.	214.	0.0	355.	585.	650.	565.	0.3	5.90
0.25%	526.	5.	203.	0.8	322.	687.	586.	569.	0.9	0.81
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	557.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	593.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=175mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	525.	5.	217.	0.0	361.	570.	653.	563.	0.3	5.90
0.25%	527.	5.	206.	0.8	328.	651.	611.	566.	0.9	0.82
0.50%	541.	5.	201.	1.5	309.	735.	539.	565.	1.5	1.55
0.75%	557.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	592.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=200mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	530.	5.	223.	0.0	370.	548.	657.	559.	0.3	5.90
0.25%	530.	5.	211.	0.8	335.	612.	633.	563.	0.9	0.84
0.50%	541.	5.	202.	1.5	310.	732.	541.	565.	1.5	1.55
0.75%	557.	5.	204.	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	592.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=14 SL=225mm

SP%	RTC	CS	W,kg	SP,kg	C,kg	A1,kg	A2,kg	A3,kg	AIR %	SP,Kg
0.00%	538.	5.	231.	0.0	383.	513.	664.	553.	0.3	5.90
0.25%	538.	5.	219.	0.9	348.	580.	639.	557.	0.9	0.87
0.50%	544.	5.	209.	1.6	321.	655.	594.	560.	1.5	1.61
0.75%	557.	5.	204..	2.3	306.	726.	533.	559.	2.1	2.29
1.00%	575.	5.	206.	3.0	303.	719.	528.	553.	2.6	3.03
1.25%	592.	5.	208.	3.8	300.	713.	523.	549.	3.0	3.75
1.50%	611.	5.	208.	4.5	298.	708.	519.	545.	3.5	4.47
1.75%	630.	5.	207.	5.2	296.	704.	516.	542.	3.9	5.18
2.00%	649.	5.	205.	5.9	295.	701.	514.	539.	4.4	5.90

FCK=16 SL= 50mm

APPENDIX E

QUESTIONAIRE FOR IDENTIFYING THE INVESTMENT AND OPERATING CHARACTERISTICS OF THE READY-MIXED CONCRETE FOR COST ANALYSES

APPLICATION DATE: 7/6/1995
FIRM CODE NO:ATMAZ INSAAT KOLL. STI.
CAPACITY : 25 m3/hour

(1) MATERIAL COSTS:

Material		Unit Price	Transportation
Diesel oil:		19040 TL/lt	--------------
Water :		-----	
Cement :		1670000 TL/Ton	70000 TL/Ton
Aggregate	No1:	300000 TL/Ton	-----
	No2:	200000 TL/Ton	-----
	No3:	200000 TL/Ton	-----

Dollar: 42900 TL DM: 30400 TL i=7%

(2) GENERAL MANAGEMENT AND TECHNICAL PERSONNEL COST:

Function	Number	Cost, TL/month	Total
Manager :	1	10000000	
Co Manager :	1	7000000	
Engineer :	---		
Technician :	---		
Accountant :	1	7000000	
Secretary :	---		
Guard :	1	5000000	
Others :	1	5000000	

Personnel Total Cost = 71.2 kgC/hour

(3) COST OF CONCRETE PLANT

(a) Concrete Plant:

Price	Economic Life	Salvage Value
2.000.000.000 TL	15 years	200.000.000 TL

Capital Recovery = 36.41 kgC/hour

(b) Personnel:

Function	Number	Cost	Total
Worker	2	6.500.000 TL/month	13.000.000 TL
			27.2 kgC/hour

(c) Maintenance Cost:

Type	Total
Various	16.83 kgC/hour

(4) COST OF PUMP

(a) Pump:

Price	Economic Life	Salvage Value
17.000.000.000 TL	20 years	5.000.000.000 TL

Capital Recovery = 255.12 kgC/hour

(b) Personnel, Operating Cost:

Function	Number	Cost	Total
Worker	2	8.000.000 TL	16.000.000 TL
			33.5 kgC/hour

(c) Maintenance Cost:

Type	Total
Various	147.4 kgC/hour

(5) COST OF TRANSMIXER

(a) Cost of Transmixer:

Price	Number	Economic Life	Salvage Value
1.500.000.000 TL	8	15-year	0 TL

Capital Recovery = 226.7 kgC/hour

(b) Personnel, Operating Cost:

Function	Number	Cost	Total
Worker	1	7.500.000 TL/month	7.500.000 TL
Driver	8	7.000.000 TL/month	56.000.000 TL
			132.9 kgC/hour

(c) Maintenance Cost:

Type	Total
Various	1047.2 kgC/hour

(6) CONCRETE PLACING AND COMPACTION TEAM

(a) Used Tools:

Price	Economic Life	Salvage Value
75.000.000 TL	------	0 TL

<u>Capital Recovery = 1.84 kgC/hour</u>

(b) Personnel:

Function	Number	Cost	Total
Worker	3		1.150.000 TL/day <u>72.2 kgC/hour</u>

(7) RENTAL PAYED

Rent = 50.000.000 TL/mounth = 104.66 kgC/hour

Total Investment and
Maintenance, Operating Cost = 2173.16 kgC/hour

= 86.93 kgC/m3 conc.