BONDING EFFICIENCY OF ROLLER COMPACTED CONCRETE WITH DIFFERENT BEDDING MIXES

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ABSTRACT

BONDING EFFICIENCY OF ROLLER COMPACTED CONCRETE WITH DIFFERENT BEDDING MIXES

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Roller Compacted Concrete (RCC) has rapidly evolved from a concept to a material and a process which is used throughout the world for faster and more economical construction of dams. Currently, there are more than 250 RCC dams, completed or under construction, in the world. On the other hand, currently, there are only two RCC dams completed (Suçatı and Cindere Dams) and two under construction (Beydağ and Çine Dam) in Turkey.

RCC dams are constructed in a series of compacted layers usually 30 cm in thickness. Therefore, appropriate bonding of successive layers is important and as a result, in between successive layers a bedding mix is often used to fill the surface voids in both the compacted layer below and the covering layer above, as well as to bond the two successive layers together.

This study presents an experimental investigation on the bonding efficiency of RCC with different bedding mixes. The Beydağ Dam RCC mixture was taken as the model for the preparation of laboratory-made RCC specimens. In the experimental study, 15 cm cubic specimens were prepared in two layers. Each layer was compacted using an electro pneumatic demolition hammer for 30 seconds. Four different time intervals between placement and compaction of two successive layers and two different bedding mix types were the selected cases for investigation. While preparing the specimens, the second layer was placed and compacted 0, 4, 8, 12 and 16 hours after the first layer was compacted. In between the two layers, two types of bedding mixes are placed in between previously compacted and freshly placed layer for joint treatment. One of the bedding mixes, having 200 kg/m^3 cement content is termed poor while other one is termed rich having 400 kg/m^3 cement content.

RCC specimens are then subjected to compressive strength, splitting tensile strength and permeability tests. As a result of the experimental program, it was found that; a rich bedding mix was a more effective bonding agent between compacted RCC layers than the poor bedding mix for all time intervals between layers. Furthermore, it was concluded that bonding efficiency of RCC is not too dependent on time interval between layer compactions up to 16 hours. Finally, splitting tensile strength and sorptivity tests are shown to be applicable test methods for determination of bonding efficiency of RCC specimens if there is a definite bedding layer in between freshly placed and formerly compacted RCC.

Keywords: *Roller Compacted Concrete, Bedding Mix, Bonding Efficiency*

ÖZ

SİLİNDİRLE SIKIŞTIRILMIŞ BETONUN FARKLI YASTIK KARIŞIMLARI İLE YAPIŞMA VERİMLİLİĞİ

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Silindirle Sıkıştırılmış Beton (SSB), kavramdan malzemeye, barajların daha hızlı ve ekonomik yapımı için dünyanın her yerinde kullanılan bir yönteme hızlı bir gelişim göstermiştir. Şu anda, dünyada 250'den fazla SSB baraj tamamlanmış veya yapım aşamasındadır. Öte yandan, şu anda, Türkiye'de sadece iki tane SSB baraj (Suçatı ve Cindere barajları) tamamlanmış ve iki tanesi (Beydağ ve Çine barajları) ise yapım aşamasındadır.

SSB barajlar genellikle 30 cm kalınlığında bir dizi sıkıştırılmış tabaka halinde inşa edilmektedir. Dolayısıyla, ardışık tabakaların uygun bir şekilde yapışması önemlidir ve bunun sonucu olarak, müteakip iki tabaka arasında alttaki sıkıştırılmış tabaka ile üstteki örten tabakanın yüzey boşluklarını doldurmak, hatta müteakip iki tabakayı birbirine yapıştırmak için bir yastık karışımı sıklıkla kullanılmaktadır.

Bu çalışma, SSB'nin farklı yastık karışımları ile yapışma verimliliğiyle ilgili deneysel bir araştırmayı sunmaktadır. Laboratuvarda üretilen SSB numunelerinin hazırlanmasında Beydağ barajı SSB karışımı model alınmıştır. Deneysel çalışmada

15 cm'lik küp numuneler iki müteakip tabaka halinde hazırlanmıştır. Her tabaka bir elektropnömatik kırıcı tabanca kullanılarak 30 saniye sıkıştırılmıştır. İki tabakanın yerleştirilip sıkıştırılması arasındaki farklı dört zaman aralığı ile farklı iki yastık karışımı tipi araştırma için seçilen parametrelerdir. Numuneleri hazırlarken, ikinci tabaka, ilk tabaka sıkıştırıldıktan 0, 4, 8, 12 ve 16 saat sonra yerleştirilip sıkıştırılmıştır. Birleşim bölgesi iyileştirmesi için, iki tip yastık karışımı önceden sıkıştırılmış ve yeni yerleştirilen iki tabaka arasına dökülmüştür. Bu yastık karışımlardan biri zayıf olarak adlandırılıp, 200 kg/m^3 çimento içermekte iken diğeri kuvvetli olarak adlandırılıp 400 kg/m^3 çimento içermektedir.

SSB numuneler sonrasında basınç dayanımı, yarmada çekme dayanımı ve geçirimlilik deneylerine tabi tutulmuştur. Deneysel programın sonucunda, zengin yastık karışımının zayıf yastık karışımına göre tabakalar arasındaki bütün zaman aralıklarında daha etkili bir yapıştırma malzemesi olduğu bulunmuştur. Bundan başka, SSB yapışma verimliliğinin 16 saate kadar sıkışmış tabakalar arasındaki süreye çok bağlı olmadığı sonucuna varılmıştır. Son olarak, SSB numunelerin yapışma verimliliğini elde etmede, yarmada çekme dayanımı ve kılcal geçirimlilik deneylerinin, yeni yerleştirilen SSB tabaka ile önceden sıkıştırılan SSB tabaka arasında belirgin bir yastık tabakası varsa, uygulanabilir test metodları olduğu gösterilmiştir.

Anahtar Kelimeler: *Silindirle Sıkıştırılmış Beton, Yastık Karışımı, Yapışma Verimliliği*

To My Parents

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CM	Cementitious Materials
CMC	Conventional Mass Concrete
CVC	Conventionally Vibrated Concrete
HEPP	Hydroelectric Power Plant
ICOLD	International Commission of Large Dams
INC	Incorporated
NMSA	Nominal Maximum Size of Aggregate
PAC	Preplaced Aggregate Concrete
PCA	Portland Cement Association
RCC	Roller Compacted Concrete
RCD	Roller Compacted Dam
SSD	Saturated Surface Dry
USACE	United States Army Corps of Engineers

CHAPTER 1

INTRODUCTION

1.1 General

Roller Compacted Concrete (RCC) emerged as a new type of construction material during the 1960s. ACI 207.5R-89 defines RCC as concrete compacted by roller therefore, the concrete mixture in its unhardened state must support a roller while being compacted [1].

RCC technique has superseded traditional methods of dam construction. By the end of the year 2008, there are more than 250 RCC dams, completed or under construction, in the world. In Turkey, currently, there are only two RCC dams (Suçatı and Cindere Dams) completed and only two under construction (Beydağ and Çine Dams).

Like conventional concrete, RCC consists of different combinations of cements and pozzolans, aggregate and sufficient water. Moreover, compared to conventional concrete, its cement content is quite low. However less water is used in RCC, less cement is required to produce an equivalent water/cement ratio of conventional concrete. Portland cement is normally the primary cementing material in RCC, although fly ash or natural pozzolans are often used as a major portion of the cementitious materials.

RCC dams are constructed in a series of compacted layers usually 30 cm in thickness. Therefore, the bonding of successive layers is important both for strength and permeation purposes. A bedding mix is often designed to fill the surface voids in both the compacted layer below and the covering layer above as well as to “glue” the two RCC layers together. The bedding mix is generally 10 mm to maximum 0.5

inch thick. However, subjects such as; the time interval for usage of bedding mix between RCC layers and the behavior of two materials together as time passes have not been investigated in detail in the history of RCC.

1.2 Objective

There are two major objectives of the study. The first objective is to investigate the effects of different bedding mixes on the hardened properties of RCC as a bonding agent between layers. Moreover, the effects of different time intervals for the application of bedding mixes is investigated as a second objective. Therefore, related to the above objectives, two types of bedding mixes with the application of four time intervals between RCC layers are selected. For comparison, unbedded specimens are also produced. Finally, the suitability of experimental methods to be used for RCC specimens are evaluated for the given cases.

1.3 Scope

This thesis consists of six chapters. Chapter 1 presents a brief introduction and states the objectives of this experimental study. Typical properties of RCC and the bedding mix, a brief history of RCC, the design methods used in RCC, Beydağ Dam RCC studies and previous research at M.E.T.U. are given in Chapter 2 through a literature survey.

Chapter 3, basically presents the experimental program. The properties of the materials used in RCC production, the properties of the compaction equipment, the test procedures (compressive strength, splitting tensile strength and sorptivity) utilized and the results of the tests are all presented in this chapter.

Based on the experimental data presented previously, the discussion of results are given in Chapter 4. Results such as compressive and splitting tensile strength test together with sorptivity tests are discussed.

Furthermore, the summary and conclusions part of the thesis is presented in Chapter 5 which summarizes the findings of discussion of the results section clause by clause.

Finally, recommendations for future studies and possible further research that will complement this thesis are provided in Chapter 6 together with the problems faced throughout the study.

CHAPTER 2

LITTERATURE SURVEY ON ROLLER COMPACTED CONCRETE

In general the development of Roller Compacted Concrete (RCC) caused a major shift in the construction practice of mass concrete dams. The traditional method of placing, compacting, and consolidating mass concrete is a slow process. However, today, improvements in equipment made the construction of RCC dams faster and, therefore, more cost-effective.

In the RCC history, materials that have been called rollcrete, large-aggregate soil-cement, rolled concrete, or cement-treated base are all considered to be RCC which describes the use of RCC for the construction of new dams and for the rehabilitation of existing dams.

ACI 207.5R-89 defines RCC as *"concrete compacted by roller compaction. The concrete mixture in its unhardened state must support a roller while being compacted [1]"*. ICOLD Bulletin 126 defines RCC as *"concrete with a no-slump consistency in its unhardened state that is transported, placed, and compacted using fill-dam construction equipment [2]"*.

RCC is a zero-slump concrete whose properties are strongly dependent on the mixture proportions and on the quality of compaction. RCC is usually mixed using high-capacity continuous mixing or batching equipment, delivered with trucks or conveyors, and spread with one or more bulldozers in layers prior to compaction [3]. Figure 2.1-2.3 shows typical placement techniques of RCC respectively. In the past, RCC was delivered mostly by dump trucks, but nowadays conveyors are also often utilized.

Figure 2.1 A view of transportation and dumping of concrete

Figure 2.2 A view of spreading of RCC layers

Figure 2.3 A view of compaction of concrete using vibrating roller

In comparing RCC with conventional concrete, less water is used and consolidation is achieved externally with steel drum vibrating compactors. Because less water is used, less cement is required to produce an equivalent water/cement ratio. Less water in the mixture leads to less drying shrinkage and less cement results in less heat generation. The reduction in drying shrinkage and heat generation, in combination, reduces cracking potential. Additionally, reduced water content and vibratory roller compaction increases its unit weight.

Portland cement is normally the primary cementing material in RCC, although fly ash or natural pozzolan are often used for a major portion of the cementitious materials.

According to Andriolo [4], RCC is concrete proportioned to support external compaction equipment. Though related to granular soil-cement, which may use similar placement techniques, it contains a larger amount of coarse aggregate and develops properties similar to conventionally placed concrete.

The maximum placement of 18 000 m^3 of RCC in one day in Tarbela Dam, in Pakistan, which is still the world's record, was a clear evidence of the potential of this new construction method [5].

2.1 Historical Development of Roller Compacted Concrete Around the World

The idea of combining placement advantages of loose materials with the advantages of concrete as a construction material in dams developed in the 1960s. RCC as a construction material was first used in a dam in 1960-1961, at the core of Shihmen Cofferdam in Taiwan. All materials used were based on concepts similar to conventional concrete except water content. The water content was based on optimum moisture content obtained from the Modified Proctor Method [4].

Between 1961 and 1965, the Alpe Gera Dam was built in Italy. The concept behind it was to reduce the cement content in the concrete mix used for the interior of the dam, where stresses are low and durability requirements are minimal. This lean concrete was consolidated by internal vibration rather than external roller compaction [4].

In 1962, Lowe suggested the application of lean concrete and the possible use of rubber or metallic compactors to compact the concrete in Shihmen Dam at the conference organized by ASCE in Omaha, Nebraska. He invented the word 'rollcrete' as an abbreviation of roller compacted concrete which was later used at Tarbela Dam in Pakistan [4].

Following the same idea about the interior of the Alpe Gera Dam, Manicougan I Dam was built in Quebec, Montreal in 1965. A richer mix was used for the upstream face of the dam. At that time, it was estimated that the system saved 20% of the cost and two-thirds of the time that would have been required to build with conventional concrete [4].

In 1970, Raphael from University of California at Berkeley presented a seminar paper about RCC development at Asilomar Conference. His paper, "*The Optimum Gravity Dam*" presented a number of ideas that were based on soil-cement theory. He proposed the concept of placement and compaction of an embankment with cement-enriched material using complex compaction equipment which was later resulted in a significant reduction of the cross section of RCC dam compared with a typical embankment dam [5]. Later Cannon took Raphael's ideas a step further. He proposed using a richer mix on the upstream and downstream faces instead of using lean mix [5].

During the 1970s, a number of organizations were involved in various trials, laboratory works and development of subjects concerning mass RCC. As a consequence, RCC dam design evolved in three different directions. These were the alternatives being developed by U.S. Army Corps of Engineers, British engineers and a Japanese research team. U.S. Army Corps of Engineers developed a lean-concrete alternative based on soils technology. British engineers focused on the high-paste method and the Japanese research team set up a new concept called RCD (Roller Compacted Dam) [5].

In 1974, U.S. Army Corps of Engineers completed the design and preliminary laboratory tests for Zintel Canyon Dam in the U.S.A., but due to funding problems, the dam was not actually constructed until 1992 [5].

In Japan, research on RCC started in 1974 and the early projects were done using the technology called RCD which was based on possible lowest cement content while satisfying strength requirements. Also some fly ash was used as an admixture.

In Brazil, RCC technology was first used in 1976 to build a concrete floor at a storage building at Itapu Dam site.

In Great Britain, research on RCC was started during the construction of the Winbleball Dam in 1979. The RCC designed during this experiments had a high paste content [6].

In U.S. another Army Corps of Engineers dam project, Willow Creek Dam was built in less than five months in 1982 and became the world's first major dam to be built entirely of RCC [5].

In Spain, RCC was first used at the Erizana Dam in 1985.

In Turkey, Çine Dam and HEPP (Hydroelectric Power Plant) which is located in Çine/Aydın was the first RCC dam started in 1996 and its construction is still underway. Suçatı Dam and HEPP which is located in Suçatı/Kahramanmaraş was the second RCC dam whose construction started in June 1998 and finished in less than 2 years. Cindere Dam and HEPP which is located in Güney/Denizli became the third RCC dam and its construction was finished in 2008. Lastly, Beydağ Dam whose construction started in Ödemiş/İzmir in 2005, became the fourth RCC dam and its construction is stil underway.

Furthermore to understand the development of RCC construction technology, it is important to note that at the end of 1980, there were only 2 completed RCC dams and at the end of 1986, there were 15 completed RCC dams in the world. Currently, there are more than 250 RCC dams, completed or under construction, in the world. Essentially, in all but a few cases where there are a significant number of inserts in the dam, RCC has effectively replaced traditional concrete for the construction of dams [2].

2.2 Properties of Roller Compacted Concrete

Some RCC mixtures can have properties and behavior similar to conventional concrete, but most of the time RCC has unique properties that can be very different from the properties or behavior of traditional concrete. RCC is usually transported by truck or conveyor belt and deposited in piles or windrows at the placement site. RCC is then spread in layers with dozers and consolidated with vibratory rollers. Due to the stiff no-slump consistency of the RCC, all or most of the formwork and associated labor required for conventional mass concrete can thus be eliminated [15].

The properties of hardened RCC are similar to those of mass concrete. However, some differences between RCC and mass concrete exist, primarily due to the differences in required strength, performance and voids content of the RCC mixtures. Most RCC mixtures are not air-entrained and also may use aggregates not meeting the quality or grading requirements of conventional mass concrete. RCC mixtures may also use pozzolans, which affect the rate of strength gain and heat generation of the mix. Because some RCC mixtures may use lower quality aggregates and lower cementitious materials contents (than conventional concretes), the range of hardened properties of RCC is wider than the range of properties of conventional concrete [3].

2.2.1 Workability

The capacity of RCC to be placed and compacted successfully without harmful segregation is called workability. Moreover, workability of RCC contains the concepts of compactability and, to some degree, moldability and cohesiveness. Workability of RCC is affected by the same factors that affect the conventional concrete (i.e., cement content, water content, the presence of chemical and mineral admixtures, and the grading, particle shape, and relative proportions of coarse and fine aggregates). However, the effect of each factor will not be the same for RCC as for conventional concrete [7].

The workability of RCC cannot be measured or judged in the same way that the placeability of conventional concrete is indexed to the slump test. The slump test is not meaningful for concrete intended for roller compaction since the correct mixture has no slump [7]. When there is sufficient paste to fill aggregate voids, workability of RCC mixtures is normally measured on a vibratory table with a Vebe apparatus in accordance with ASTM C 1170 [3].

The ASTM modified Vebe device which is given in Figure 2.4, sets a 22.7 kg flat surcharge plate over a fresh sample of the mix after the RCC has been placed into the cylindrical Vebe container. The diameter of the plate is slightly smaller than the inside diameter of the Vebe container. The length of time required for the weight to compact the RCC down enough to cause paste to come up around the rim of the plate is recorded as Vebe time [7].

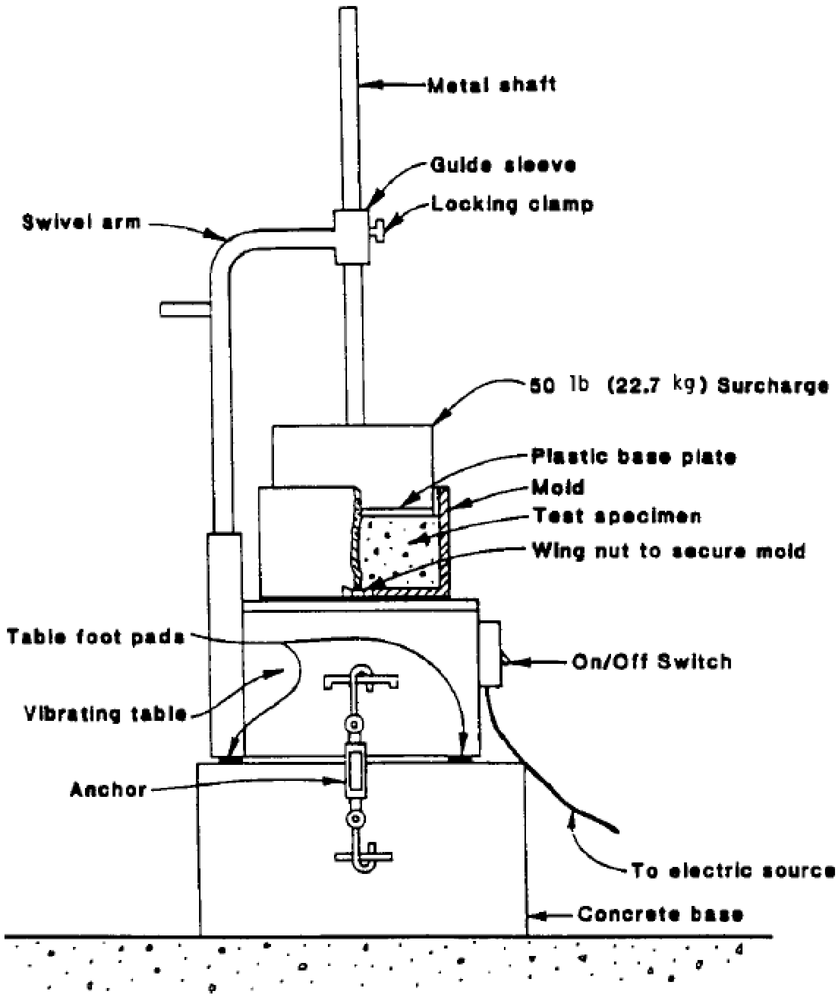


Figure 2.4 Schematic description of Vebe test apparatus [3]

RCC mixtures generally have a Vebe time of 10 to 45 seconds to satisfy the degree of workability necessary for ease of compaction and production of uniform density from top to bottom of the lift, for bonding with previously placed lifts, and for support of compaction equipment [3]. However, it was realised in literature that, RCC mixtures have been proportioned with a wide range of workability levels other than what is provided above. Some RCC mixtures have contained such low paste volume that workability could not even be measured by the Vebe apparatus. This is particularly true of those mixtures designed more as a cement stabilized fill. Workability of these types of mixtures are judged by observations during placement and compaction, together with compacted density and moisture content measurements.

According to Schrader [6], dry consistency RCC mixtures which are at or near optimum moisture have Vebe times between 30 to 60 seconds, whereas wet consistency mixes have between 10 to 20 seconds. He concluded further that for embankment materials and soils there is an “optimum” moisture where the greatest density and mimimum voids occurs. The “optimum” moisture should be considered as the absolute minimum water content for the mix, regardless of the cement content. For RCC aggregates, the “optimum” water content is generally about 100 kg of water per cubic meter of compacted material.

Advantages of the drier consistency mixtures include somewhat greater economy through more efficient use of cementing materials and less surface deterioration and deformation during placement [7]. The water demand for a specific level of workability will be influenced by the size, shape, texture and gradation of aggregates, the volume and nature of cementitious and fine materials [3].

2.2.2 Unit Weight

The unit weight of RCC depends primarily on the specific gravity of the aggregate and the amount of voids in the RCC mass. The lack of entrained air and lower water content of many RCC mixtures results in a slightly higher density when compared to conventional air-entrained mass concrete made with the same aggregate. Fully compacted RCC has a low air content (generally 0.5 to 2.0%) and a low water content. More solids occupy a unit volume and the increased density is approximately 1 to 3% more than conventional concrete and routinely exceeds 2400 kg/m^3 [3].

2.2.3 Compressive Strength

Compressive strength tests are performed in the design phase to determine mixture proportion requirements, and also to optimize combinations of cementitious materials and aggregates. For RCC, compressive strength is used to satisfy design loading requirements and also as an indicator of other properties such as durability. Tests of cores from test sections may be used to evaluate strength of RCC for design purposes, and also to evaluate the effects of compaction methods. During construction, compressive strength tests are used to confirm design properties as a tool to evaluate mixture variability. Cores are also used to further evaluate long-term performance [3]. Like conventional concrete, the compressive strength of RCC is predominantly affected by the water content, cementitious material content, properties of the cementitious materials, the aggregate grading, and the degree of compaction. Use of pozzolans can delay the early strength development of RCC. Higher pozzolan contents cause lower early strength. However, mixtures proportioned for later age strengths, such as at 180 days or 1 year, can use significant quantities of pozzolan [3].

Furthermore, RCC mixtures with low cementitious contents may not achieve required strength levels if aggregate voids are not completely filled. For these mixtures, it was shown that the addition of nonplastic fines or rock dust has been beneficial in filling voids, thus increasing the density and strength. Use of plastic (clay) fines in RCC mixtures has been shown to adversely affect strength and workability and therefore is not recommended [3].

Moreover, significant differences in compaction will affect the strength of RCC in both the laboratory and in core samples from in-place construction. For laboratory specimens, the energy imparted to the fresh mixture must be sufficient to achieve full compaction, or strength will not reach the required level due to uneliminated voids. The compactive effort in the laboratory will be compared to cores during the test section phase of construction, provided that the test section has sufficient strength for cores to be taken. The compressive strength of concrete will also decrease due to insufficient compaction, usually near the bottom of the lift. Not only does this affect compressive strength, but also bond strength and joint seepage. Compressive strength will also decrease due to delays in completing compaction [3].

Table 2.1 presents various properties of RCC mixes utilized throughout the world [3]. As shown in that table both cement and fly ash were utilized in most of the cases. Minimum and maximum cement content in Willow Creek Dam was observed to be 47 kg/m^3 and 187 kg/m^3, respectively. Fly ash was utilized as high as 207 kg/m^3. The compressive strengths observed at the end of one year ranged from 8.6 MPa to 51.0 MPa.

Table 2.1 Compressive strength of some RCC dams [3]

Dam/Project	Cement (kg/m^3)	Pozzolan (kg/m^3)	w/cm	NMSA (mm)	Compressive Strength (MPa), at test age				
					7 days	28 days	90 days	180 days	365 days
Camp Dyer (USA)	82	81	0.55	38.1	6.10	10.10	-	-	25.40
Conception (Honduras)	90	0	1.03	76.2	4.00	5.50	7.60	8.80	-
Galesville (USA)	53	51	1.09	76.2	2.10	4.00	7.00	-	11.20
	65	68	0.84	76.2	2.90	5.70	9.40	-	-
Middle Fork (USA)	66	0	1.43	76.2	-	8.80	11.40	-	-
Santa Cruz (New Mexico)	76	75	0.67	50.8	7.50	18.80	22.20	-	30.50
Stacy Spillway (USA)	125	62	0.82	38.1	-	18.10	21.40	-	-
Stagecoach (USA)	71	77	0.93	50.8	1.50	2.40	-	6.80	8.60
Upper Stillwater (USA)	79	173	0.37	50.8	10.80	17.70	24.80	38.50	48.10
	94	207	0.30	50.8	14.10	23.60	29.00	38.10	51.00
	79	173	0.39	50.8	7.40	12.60	17.90	-	44.10
	93	206	0.33	50.8	9.20	15.40	21.40	-	46.50
Urugua-I (Uruguay)	60	0	1.67	76.2	-	6.40	8.10	-	9.60
Willow Creek (USA)	104	0	1.06	76.2	6.90	12.80	18.30	-	26.10
	104	47	0.73	76.2	7.90	14.20	27.30	-	28.60
	47	19	1.61	76.2	4.00	8.10	11.90	-	18.10
	187	80	0.41	38.1	14.00	23.50	30.80	-	39.90

Compressive strength from cores of RCC follows the standard relationship of core strength to cylinder strength from conventional concrete, but may vary more widely depending on mixture workability, compaction effectiveness, cylinder preparation methods, and other factors. Core and cylinder (l / d = 2) testing on a number of RCC dams is reported to provide an overall average of core compressive strength equal to about 75% of the equivalent age cylinder compressive strength [7].

In some projects where low workability RCC mixtures were used, the cylinder strengths have been lower than the core compressive strengths due to difficulty in adequately compacting test cylinders (ASTM C1435-99 [8]). Coefficient of variations (COV) of RCC compressive strength specimens cast during construction have varied widely, depending primarily on the mixture workability. COV is generally used more frequently than standard deviation, due to the commonly low-strength mixtures used on dams. Like conventional mass concrete, COV of RCC tends to decrease with later ages of testing [7].

According to Andriolo [4], it is very difficult to discuss compressive strength because, it depends on the cementitious material content (cement + pozzolanic material). A normal way that could be used to correlate these parameters (cement and pozzolanic material content) is based on a mix efficiency factor (η) which is defined as:

$$\eta = \frac{\text{Compressive Strength in kgf/cm}^2}{\text{Cementitious Materials in kg/m}^3}$$

In general, a mix efficiency at later ages is higher for RCC than comparable conventional concrete, meaning that a desired compressive strength of RCC can be obtained by using lower cementitious content, particularly using Portland cement and higher pozzolanic material content. These types of mixes develop higher strength due to the best combination of cement and pozzolanic material [4].

Tangtermsirikul et al. [10] have studied to find a compressive strength model for Roller Compacted Concrete with fly ash. The model was formulated based on quantities of concrete ingredients, chemical compositions and physical properties of cement and fly ash. They reported that at room temperature of 28 ± 3°C the proposed model could be used to predict compressive strength of the tested mixtures of RCC with fly ash designed for dams and road pavements at the ages between 3 and 91 days with satisfactory accuracy.

2.2.4 Tensile Strength

Tensile strength of RCC is required for design purposes, including dynamic and thermal analysis. The ratios of tensile-to-compressive strength for parent (unjointed) RCC mixtures have typically ranged from approximately 5 to 15%, depending on aggregate quality, strength, age, and test method. Mixtures with low cementitious materials content, or those with lower-quality or coated aggregates, or both, will have corresponding lower direct tensile strengths. The ratio of direct tensile strength to compressive strength of both RCC and conventional mass concrete will usually decrease with increasing age and compressive strength [3].

The direct tensile strength of RCC is less than the splitting tensile strength of unjointed RCC. The direct tensile strength of RCC lift joints (the horizontal line in between compacted RCC layers) is not only dependent on the strength of the mixture, but also on the speed of construction, the lift-joint surface preparation, degree of compaction and segregation at the lift interface, and the use of a bonding mixture on the lift surface. Inadequate lift-surface cleanup, poor consolidation, or both, can drastically reduce the direct tensile strength across lift lines. With adequate attention to lift surface preparation, the direct tensile strength of RCC lift-joints average has been assumed to about 5% of the compressive strength. The splitting tensile strength of the parent (unjointed) RCC has been assumed to be approximately 10 percent of the compressive strength [3].

Lift joints are the weakest locations in RCC, as in conventional mass concrete, structures. Hence, the tensile strength at the lift joints is the critical tensile property for RCC. Direct tensile strength is the pertinent tensile test for lift joint tensile strength. Splitting tensile testing of horizontal cores has been used to establish joint strength; however, identification and location of the joint in the central portion of the core, for correct performance of the test, is reported to be very difficult [7].

2.2.5 Permeability

The permeability of RCC is largely dependent upon voids in the compacted mass, together with porosity of the mortar matrix, and therefore is almost totally controlled by mixture proportioning, placement method, and degree of compaction. RCC will be relatively impervious when the mixture contains sufficient paste and mortar with an adequate fine-particle distribution that minimizes the air void system. In general, an unjointed mass of RCC proportioned with sufficient paste will have permeability values similar to conventional mass concrete. Test values typically range from 0.15 to 15 x 10^{-11} m/s. High cementitious mixtures tend to have lower permeability than low cementitious mixtures [3].

If seepage occurs in RCC dams, it usually occurs mainly along the horizontal lift joints rather than through the compacted and unjointed mass. If seepage occurs along horizontal lift joints, it also indicates a reduction in shear and tensile strength at this location [3]. For example at Willow Creek (USA), water is reported to appear on the downstream face of the dam 12 hours after impounding [2].

According to Andriolo, the permeability coefficient of tested construction joints ranged from 1×10^{-9} m/s to 1×10^{-11} m/s, which is comparable to that of conventional concrete. As with the permeability apparatus at Capanda Laboratory it was shown that RCC permeability coefficients ranges from 10^{-6} m/s to 10^{-12} m/s with cementitious content from 60 kg/m^3 to 250 kg/m^3, as compared to 10^{-9} m/s to 10^{-12} m/s for CVC, with similar cementitious content [4].

Figure 2.5 shows the results of in-situ permeability testing on 49 different water-retaining RCC structures from 18 different countries taken from ICOLD Bulletin 126 [2]. Total in-situ permeability (including that at joints) ranging from 10^{-4} to 10^{-13} m/s has been found and there is a consistent relationship between the permeability and the cementitious content [2].

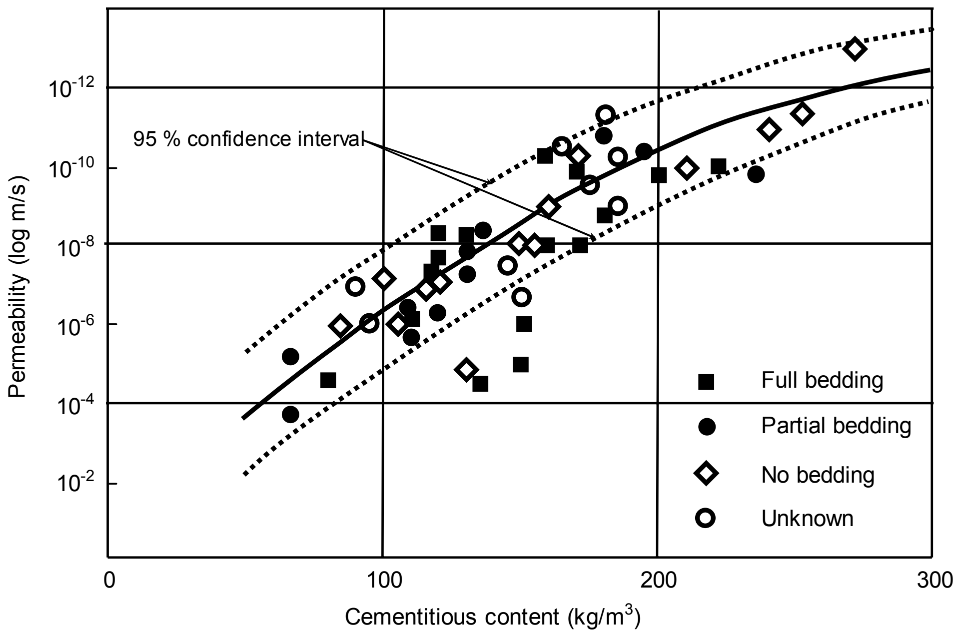


Figure 2.5 Relationship between total in-situ permeability (including at joints) and cementitious content for concretes from RCC structures [2]

Measured RCC permeability values have a very large range because of the wide range of mixtures used and the wide range of density achieved in structures and test specimens due to the use of cores and cylinder specimens and the variety of permeability tests used.

It was also shown by Krempel and Andriolo that the use of ground fines can also improve the impermeability, although the effect is somewhat less than cementitious materials [11].

2.2.6 Durability

RCC, like conventional mass concrete, is subject to potential deterioration due to the effects of abrasion/erosion, freezing and thawing, and other factors such as alkali-silica reaction, and sulfate attack [3].

Abrasion/erosion resistance of RCC is primarily governed by its compressive strength and the quality of the aggregate it contains. RCC pavements at heavy-duty facilities such as log storage yards and coal storage areas have shown little wear from traffic and industrial abrasion under severe conditions [3]. The North Fork Toutle River Debris Dam spillway showed only surface wear after being subjected to extraordinary flows of highly abrasive grit, timber and boulders. This structure was constructed with RCC containing good quality small-size aggregate and a higher cement content than normally used in mass RCC construction (300 kg/m^3). Additional abrasion/erosion damaged the top lift of the RCC spillway [3].

ASTM C 1138 has been used to evaluate the erosion resistance of both conventional concrete and RCC [12]. This procedure results in values of concrete volume (or average depth) loss at 12 hours increments up to conclusion of the test at 72 hours. Abrasion-erosion percent loss after 72 hours can be expected to range from about 3 to 15% (higher values for lower strength mixtures) for workable RCC mixtures with good to excellent quality aggregates [7].

RCC mixtures do not normally have entrained air, and consequently will not have a high freeze-thaw resistance in a critically saturated moisture condition. Many examples of good field performance is reported to exist. However, RCC without air-entrained admixture subjected to ASTM C 666, Procedure A, is reported to perform very poorly [13].

Gao et al. have studied frost resistance of RCC with fly ash. They have found a relationship between the air void spacing factor and the frost resistance of RCC. When the spacing factor is below 0.4 mm, high frost resistance RCC with fly ash is obtained and it is unnecessary to prescribe an air void of spacing factor less than 0.25 mm for RCC [14].

2.2.7 Heat Generation

RCC mixture proportioning for massive structures must consider the heat generation of the cementitious materials. To minimize the heat of hydration, care should be taken in the selection and combination of cementing materials used. In cases where pozzolan is used, it may be worthwhile to conduct heat of hydration testing on various percentages of cement and pozzolan to identify the combination that generates the minimum heat of hydration, while providing satisfactory strength, prior to proportioning the mixture. The amount of cementitious material used in the mixture should be no more than necessary to achieve the necessary level of strength. Proportioning should incorporate those measures which normally minimize the required content of cementitious material, such as appropriate NMSA (nominal maximum size aggregate) and well-graded aggregates [3].

Studies of the heat generation and temperature rise of massive RCC placements indicate that the sequential and rapid placement of thin layers can have a beneficial effect on crack reduction due to the more consistent temperature distribution throughout the mass when compared to more traditional ways of placing large volumes of concrete [7].

2.3 Materials

RCC differs from traditional concrete principally in that it has a consistency that will support a vibratory roller and an aggregate grading and paste content suitable for compaction by such a roller. The objective of the selection of the materials for, and design of the mixture proportions of, an RCC is to provide a stable concrete that meets all the in-situ strength, durability, and permeability requirements of the structure [2].

A wide range of materials can be used in the production of RCC. However, because some material constraints may not be necessary for RCC, the application is less demanding, more material options and subsequent performance characteristics are possible [3].

Materials used for RCC include cementitious materials (Portland cement and pozzolans such as fly ash), aggregates, water, and admixtures. This section will summarize the properties of ingredients that are used in RCC production.

2.3.1 Cements

RCC can be made with any of the basic types of Portland cement. For mass applications, cements with a lower heat generation than ASTM C 150 [16], Type I are beneficial. They include ASTM C 150, Type II (moderate heat of hydration) and Type V (sulfate-resistant) and blended cements as described in ASTM C 595 [17], Type IP (Portland-pozzolan cement) and Type IS (Portland-blast furnace slag cement). Strength development for these cements is usually slower than for Type I at early ages, but higher strengths than RCC produced with Type I cement are ultimately produced [3].

Heat generation due to hydration of the cement is typically controlled by use of lower heat of hydration cements, use of less cement, and replacement of a portion of the cement with pozzolan or a combination of these. On the other hand, reduction of peak concrete temperature may be achieved by other methods, such as reduced placement temperatures. The selection of cement type is considered regarding the economics of cement procurement. For small and medium sized projects, it may not be cost effective to specify a special lower heat cement which is not locally available. Due to the high production capability of RCC, special attention may be required to ensure a continuous supply of cement to the project [3].

Cementitious contents used in RCC dams have ranged from 60 kg/m^3 of cement used for the Urugai Dam in Argentina to 248 kg/m^3 for the predominant mix at Upper Stillwater Dam in U.S.A. [5].

The proportion of the various types of cement that have been used in RCC dams are shown below. The data were based on the 157 RCC dams that had been completed by the end of 1996. The majority of the dams for which the type of cement is not known are relatively small and it is probable that the cement used was Ordinary Portland cement [2].

- Ordinary Portland cement (ASTM Type I) (29.3%)
- Moderate-heat cement (ASTM Type II) (28.7%)

- Portland pozzolan cement (fly ash) (3.8%)
- Portland pozzolan cement (natural pozzolan) (7.0%)
- Portland blast-furnace slag cement (1.3%)
- Sulphate-resisting cement (ASTM Type V) (1.9%)
- None (4.5%)
- Unknown (23.6%)

Shouxian et al. [18] have studied the properties of low Portland cement clinker content RCC and found that RCC mixtures using low heat of hydration cement in which fly ash was used to provide 67% of the cementitious content had a compressive strength of 18 MPa at age of 90 days. Moreover, RCC containing 26 kg/m^3 Portland cement clinker had low heat of hydration, therefore temperature control measures could simplify to speed up the construction.

2.3.2 Pozzolans

At first, the selection of a pozzolan suitable for RCC should be based on its conformance with ASTM C 618 [19]. Pozzolans meeting the specifications of ASTM C 618 for Class C, Class F, and Class N have been successfully used in RCC mixtures. Class F and Class N pozzolans are usually preferred, since they normally contribute less heat of hydration than Class C and have greater sulfate resistance. For Class C pozzolans, more attention may be needed with regard to setting time, sulfate resistance, and free lime content. The use of pozzolan will depend on required material performance as well as on its cost and availability at each project site [3].

Use of a pozzolan in RCC mixtures may serve one or more of the following purposes:

- As a partial replacement for cement to reduce heat generation as well as cost
- As an additive to provide supplemental fines for mixture workability and paste volume

- As a partial replacement for cement to increase durability

The rate of cement replacement may vary from 0 to 80 percent, by mass. RCC mixtures with a higher content of cementitious material often use larger amounts of pozzolan to replace Portland cement in order to reduce the internal temperature rise that would otherwise be generated and consequently reduce thermal stresses [3].

In RCC mixtures that have a low cement content, pozzolans have been used to ensure an adequate amount of paste for filling aggregate voids and coating aggregate particles. Pozzolan may have limited effectiveness in low-cementitious content mixtures with aggregates containing deleterious amounts of clay and friable particles. While the pozzolan enhances the paste volume of these mixtures, it may not enhance the long-term strength development because of insufficient availability of calcium hydroxide released from the Portland cement for a pozzolanic reaction [3].

Class F pozzolans, especially at cool temperatures, generally delay the initial set of RCC mixtures, contributing to low early strength, but extending the working life of the freshly compacted RCC layer. In high pozzolan-content RCC mixtures, the heat rise may continue for up to 60 to 90 days after placing [3].

Kunhe et al. [20] studied the late age properties of RCC with low cement content and high class F fly ash content. It was found that the hydration of class F fly ash would proceed with increasing age and the pore structure of RCC was improved continuously.

Moreover, in another study it was found that when the content of fly ash increased from 0 to 30% and 50%, the compressive strength of RCC decreased at early ages of 7 and 28 days, but with 50% fly ash strengths are higher than with 30% fly ash or without fly ash at 90 days [21].

2.3.3 Aggregates

The selection of aggregates and the control of aggregate properties and grading are important factors influencing the quality and uniformity of RCC production. Aggregates similar to those used in conventional concrete have been used in RCC. However, aggregates that do not meet the normal standards or requirements for conventional concrete have also been successfully used in RCC dam construction [3].

Marginal aggregates are those aggregates that do not meet traditional standards, such as ASTM C 33, regardless of the method of construction [22]. Limits on physical requirements and on deleterious materials for aggregates to be used in RCC for a specific application should be established prior to construction, based on required concrete performance and demonstrated field and laboratory evaluations. The majority of RCC projects have been constructed with aggregates meeting all of the ASTM C 33 requirements, with the exception of an increased amount of fines passing the No. 200 (0.075 mm) sieve [3].

Aggregates of marginal quality have been used in RCC on some projects because they were close to the site and thereby the most economical source available. The design of the structure must accommodate any change in performance that may result. On some projects, the use of aggregates of lower physical strength has produced RCC with satisfactory creep rates, modulus of elasticity, and tensile strain capacity. These properties are desirable for mass-concrete applications where lower concrete strength can be tolerated. If practical, lower-quality aggregates are best used in the interior of dams where they can be encapsulated by higher-quality concrete, especially in freeze thaw areas [3].

In conventional concrete, the presence of a significant quantity of flat and elongated particles is usually undesirable. However, RCC mixtures appear to be affected less by flat and elongated particles than conventional concrete mixtures. This peculiarity is because vibratory compaction equipment provides more energy than traditional consolidation methods, and because the higher mortar content in RCC mixtures tends to separate coarse aggregate particles. The U.S. Army Corps of Engineers currently has a limit of 25% on the allowable content of flat and elongated particles in any size group. The use of manufactured aggregate (crushed stone) has been found to reduce the tendency for segregation, as compared to rounded gravels [3].

A basic objective in proportioning any concrete is to incorporate the maximum amount of aggregate and minimum amount of water into the mixture, thereby reducing the cementitious material quantity, and reducing consequent volume change of the concrete. This objective is accomplished by using a well-graded aggregate with the largest maximum size which is practical for placement. The proper combination of materials should result in a mixture that achieves the desired properties with adequate paste and a minimum cementitious content. However, in RCC mixtures, the potential for segregation and the means of compaction must also be primary considerations in selecting the maximum size of aggregate. Early projects in the U.S. used a 75 mm NMSA; however, a 50 mm NMSA is less prone to segregation and is becoming more widely used [3].

The combined aggregate gradation is often selected to minimize segregation. The key to controlling segregation and providing a good compactable mixture is having a grading that is consistent and contains more material passing the No. 4 (4.75 mm) sieve than typical in conventional concrete of similar nominal maximum size aggregate. Table 2.2 provides typical combined aggregate grading for various projects taken from ACI 207.5R-99 [3].

Table 2.2 Combined aggregate grading for RCC from various projects in U.S. [3]

Sieve Size	Willow Creek (USA)	Upper Stillwater (USA)	Christian Siegrist (USA)	Zintel Canyon (USA)	Stagecoach (USA)	Elk Creek (USA)
	% Passing					
100 mm	-	-	-	-	-	-
75 mm	100	-	-	-	-	100
62 mm	-	-	-	100	-	96
50 mm	90	100	-	98	100	86
37.5 mm	80	95	100	91	95	76
25 mm	62	-	99	77	82	64
19 mm	54	66	91	70	69	58
9.5 mm	42	45	60	50	52	51
4.75 mm	30	35	49	39	40	41
2.36 mm	23	26	38	25	32	34
1.18 mm	17	21	23	18	25	31
0.60 mm	13	17	14	15	15	21
0.30 mm	9	10	10	12	10	15
0.15 mm	7	2	6	11	8	10
0.075 mm	5	0	5	9	5	7

2.3.3.1 Fine Aggregates

The grading of fine aggregate strongly influences paste requirements and compactability of RCC. It also affects water and cementitious material requirements needed to fill the aggregate voids and coat the aggregate particles. RCC mixtures having a sufficient cementitious materials content and paste volume, ASTM C 33 fine-aggregate grading can be used. It can be determined when the mixtures are proportioned [3].

2.3.3.2 Coarse Aggregates

The selection of a nominal maximum size aggregate should be based on the need to reduce cementitious material requirements, control segregation, and facilitate compaction. Most RCC projects have used a NMSA of 37.5 mm to 75 mm. There has typically not been enough material cost savings from using aggregate sizes larger than 75 mm to offset the added batching cost and cost of controlling the increased segregation problems associated with the larger aggregates. NMSA has little effect on compaction when the thickness of the placement layers is more than 3 times the NMSA, segregation is adequately controlled, and large vibratory rollers are used for compaction [3].

Grading of coarse aggregate usually follows ASTM C 33 size designations. Cost savings can be realized by combining two or more size ranges such as ASTM C 33 size designations 357 or 467 for 50 mm to No. 4 (4.75 mm) and 37.5 mm to No. 4 (4.75 mm), respectively. However, as the size range increases, it becomes increasing difficult to avoid segregation of the larger particles during stockpiling and handling of this aggregate. Aggregate for RCC have used a single stockpile or been separated into as many as five aggregate sizes. Some projects simply use a coarse and a fine aggregate stockpile [3].

The design engineer must weigh the potential cost savings in a reduction in number of stockpiles and separate handling and weighing facilities against the potential for increased variation in aggregate grading and its impact on uniformity of consistency, strength, on bonding, and on permeability of the resulting RCC [3].

According to data, based on 128 of the 157 RCC dams which had been completed at the end of 1996 which is taken from ICOLD Bulletin 126, the maximum sizes of aggregates are proportioned as follows;

- 125-150 mm 6.3%
- 100-124 mm 0.8%
- 80-99 mm 36.7%
- 60-79 mm 29.7%
- 45-59 mm 14.1%
- 30-44 mm 10.9%
- < 29 mm 1.5%

All the 100 mm+ aggregates have been used in RCD dams. The most popular maximum size is in the 75- to 80-mm size, although there seems to be a trend towards smaller sizes because of the problem of segregation. The maximum size is tending towards 50 to 60 mm for crushed aggregate and about 40 to 50 mm for natural gravel. The maximum size of aggregate is not related to layer thickness nor compaction machinery. Compactability is governed primarily by the workability of the concrete. It should also be noted that less-workable mixes tend to segregate more than more-workable mixes, with a modified Vebe time less than 20 seconds. Modern vibratory rollers can compact rock-fill in layers of more than one meter to a high density with a maximum particle size of 400 mm and more [2], therefore compaction of 50 - 60 mm will not be a problem.

2.3.3.3 Fines

In low-cementitious materials content mixtures, supplemental fines, material passing the No. 200 (0.075 mm) sieve, are usually required to fill all the aggregate void spaces. Depending on the volume of cementitious material and the NMSA, the required total minus No. 200 (0.075 mm) fines may be as much as 10% of the total aggregate volume, with most mixtures using approximately 3 to 8%. Characteristics of the fines and fines content will affect the relative compactability of the RCC mixture and can influence the number of passes of a vibratory roller required for full compaction of a given layer thickness. Regardless of whether it is accomplished by adding aggregate fines, cement, pozzolan, or combination of these, most compactable RCC mixtures contain approximately 8 to 12% total solids finer than the No. 200 (0.075 mm) sieve by volume, or 12 to 16% by mass. The fines fill aggregate void space, provide a compactable consistency, help control segregation, and decrease permeability. Including aggregate fines in low-cementitious paste mixtures allows reductions in the cementitious materials content. Excessive additions of aggregate fines after the aggregate voids are filled typically are harmful to the RCC mixture because of decreases in workability, and increased water demand and subsequent strength loss [3].

When adding aggregate fines to a mixture, another consideration is the nature of the fines. Crusher fines and silty material are usually acceptable. However, clay fines, termed plastic fines, can cause an increase in water demand and a loss of strength, and produce a sticky mixture that is difficult to mix and compact [3].

In Japan, Suzuki et al. have showed that by mixing the filler of 7.5% quantity, the vibrating compacting value (obtained from vibrating hammer test in seconds used for granular soils) of RCD was dropped a quantity, and compacting become easy and the compressive strength was increased [23].

There are exceptions where the fines have not been beneficial, or where there is a very clear optimum content or clear maximum that should not be exceeded. For example, the Tongue River tests showed that it would have been appropriate to limit the maximum amount of fines to 7% rather than 8%. Another example is the Agos project. Tests with those materials showed that added fines which were manufactured from the primarily greywacke gravels, had a very slight negative effect on strength [6].

2.4 Mix Design Methods

There are a number of methods that can be used for the selection of the mixture proportions of RCC. Most of these fall under two general headings; the "*concrete*" approach in which the water/cementitious ratio is considered, and the "*soils*" approach in which the mixture is designed using a moisture/density relationship. Both approaches are intended to produce quality concrete suitable for roller compaction.

RCC mixture proportions follow the convention used in traditional concrete that is, identifying the mass of each ingredient contained in a compacted unit volume of the mixture based on saturated surface dry (SSD) aggregate condition. A practical reason for use of this standard convention is that most RCC mixing plants require that mixture constituents be so identified for inputs in the batching-control system.

During the design of the early RCC dams, both of these approaches were being used. However in recent years there has been a swing towards the concrete approach in a similar way to the swing towards RCC containing higher cementitious contents. Nevertheless the “soils” approach is still being used by some designers [2].

The two mix design methods that fall within the soils approach will be called the lean RCC method and the simplified soils methods. They both start with a desired grading for the aggregates and involve the preparation of cylinders with varying cementitious contents to determine strength or other properties. Differences between two methods center on how the moisture or water content for the mix is determined and the method for preparation of laboratory test specimens [5].

High paste method, Japanese RCD method and the Corps of Engineers’ method constitute the concrete approach methods. Because all of the methods are based on a Vebe time, the basic premise of these methods is that the volume of paste must exceed the voids in the aggregate. Therefore, there is a greater need to closely control the aggregate grading to minimize voids and the amount of paste required. All involve proportioning mixes using absolute volume concepts in which the weights and specific gravities of all materials are used to calculate a unit volume of concrete. Concrete approach mix design methods usually involve fixing all but one of the basic materials (cementitious materials, water, or aggregate content) and then varying that component until the desired consistency or required properties are achieved. Each variable can be adjusted this way to optimize mix components [2].

2.4.1 Soils Approach

2.4.1.1 Lean RCC Method

This method is advocated by Schrader [6] and has been used for most lean RCC dams. It starts with a fixed aggregate grading, varies cementitious contents, and compares results, primarily compressive strength, with RCC requirements.

After selecting the NMSA for the most economical usable gradation, amount of water used for laboratory trial mixes is determined by observing the consistency of mixes of varying water contents and by relying on past experience. The water content is set somewhere between the point on the dry side where voids are no longer visible on the side of laboratory cylinders, and, on the wet side, before the mix has a rubbery appearance. After fixing the aggregate and water content, laboratory cylinders are prepared with varying cementitious contents.

The mix design program prepared by the lean RCC method thus provides a family of curves that indicate the effects of various cementitious contents on compressive strength at various ages. The cement content can be selected to meet requirements with consideration of factor of safety and coefficient of variation. Once a cement content is selected, additional tests may also be performed with varying aggregate types or gradings, especially the percentage of fines passing No. 200 (0.075 mm) sieve [5].

2.4.1.2 Simplified Soils Method

This method is explained as Maximum Density Method in ACI 207.5R-99. The method is quite similar to the lean RCC Method in that it starts with a fixed aggregate grading and involves a test program of varying cementitious contents and comparing results once a water content is determined. Instead of determining the water content by Vebe time or visual performance, the desired water content is determined by moisture-density relationship of compacted specimens, using ASTM D 1557, Method D [24].

Variations of this method can also be used depending on the mixture composition and nominal maximum size of aggregate. Compaction equipment may be a standard drop hammer, some variation of this equipment better suited for larger-aggregate mixtures, or an alternate tamping/vibration method that simulates field compaction equipment and obtains similar densities [3].

In this method, a series of mixtures for each cementitious materials content is prepared and batched using a range of water contents. Each prepared mixture is compacted with a standard effort. The maximum density and optimum water content are determined from a plot of density versus water content for the compacted specimens at each cementitious materials content. The actual water content used is usually slightly higher (an additional approximately 1%) than the optimum value determined in the laboratory, to compensate for moisture loss during transporting, placing, and spreading. RCC specimens are then made at the optimum or the designated water content for strength testing at each cementitious materials content [3].

2.4.2 Concrete Approach

2.4.2.1 High Paste Method

The method was developed by Dunstan and modified by U.S. Bureau of Reclamation for the design of the Upper Stillwater Dam in the U.S. The resulting mixtures from that testing program generally contained high proportions of cementitious materials, high pozzolan contents, clean and normally graded aggregates, and high-workability. The purpose of the Upper Stillwater Dam mixtures was to provide excellent joint bond strength and low joint permeability by providing sufficient cementitious paste in the mixture to enhance performance at the lift joints [3].

The high paste method involves determining w/cm and fly ash cement ratios for the desired strength level and strength gain. The optimum water, fine aggregate, and coarse aggregate ratios are determined by trial batches, evaluating the Vebe consistency for a range of 10 to 30 sec. The required volumes and mass of aggregate, cement, pozzolan, water, and air are then calculated [3].

In designing a mix for a high paste content RCC dam, two conflicting requirements must be resolved. Sufficient cementitious material is needed to achieve a low permeability and assure the bond between successive lifts of RCC. At the same time, the volume changes produced by heat generated by the cementitious materials must be minimized. The problem has been solved with liberal substitutions of pozzolan for cement, assuming a suitable pozzolan is available at a reasonable cost [5].

The steps in the mix design procedure used by the Bureau of Reclamation are [5]:

1) Determine the densities and specific gravities of the cement (C), fly ash (FA), coarse aggregate (CA), water (W), and sand together with the void ratio of the total aggregate.

2) Determine a required W/(C + FA) ratio by weight based on the design compressive strength requirements at a certain age. For 29.7 MPa at one year, a W/(C + FA) of 0.50 is required, whereas for 15.9 MPa at one year the W/(C + FA) is 0.70.

3) Determine a relationship of C to FA that will produce the desired compressive strength within a specified time. For a one year strength, Bureau of Reclamation uses 25% cement and 75% fly ash. Now, proportions of cement, fly ash and water can be calculated for a unit paste (C + FA + W) volume.

4) Depending on the time allowed for an exposed lift in the dam, a paste/mortar (p/m) ratio is selected. For a lift age between 12 and 24 hours, a p/m ratio of 0.39 is used.

5) Determine a mortar percentage based on the requirement that the volume of mortar should exceed the volume of voids by 5 to 10% ; 7% is a good starting point.

6) The coarse aggregate percentage can now be calculated by subtracting the mortar percentage from 1.0.

7) Assuming an entrapped air volume of 1.5%, all the necessary have been determined to calculate batch weights for 1 m^3 of RCC based on saturated surface dry condition of the aggregates.

8) A trial mix is proportioned in the laboratory and a Vebe time is measured. If the Vebe time is not in the desired range, adjustments are made in the mix, mainly in water content. A water content change initiates revisions in other material proportions, and the mix is adjusted until all basic requirements, including consistency, are satisfied.

9) The mix can be further refined by more testing. In order to study various combinations of components such as FA/C, W/(C + FA), (C + FA)/sand, or various sand gradations, Bureau of Reclamation laboratory uses 51 mm square mortar cubes while changing one variable and keeping others constant.

2.4.2.2 Japanese RCD Method

The Japanese roller compacted dam (RCD) method was developed by Japanese engineers and is used primarily in Japan. Criteria for mixes designed for RCD method include [5]:

1) Cement content should be as low as possible while being consistent with strength requirements. Some fly ash should be used as an mineral additive to reduce heat of hydration and mixing water requirements.

2) A sand/aggregate ratio higher than for conventional mass concrete should be used to reduce segregation and to facilitate compaction by a vibratory roller.

The method incorporates the use of a consistency meter. The consistency meter is similar to the Vebe apparatus in that RCC mixture is placed in a container and vibrated until mortar is observed on the surface. The device is sufficiently large to allow the full mixture, often 150 mm NMSA, to be evaluated rather than having to screen out the oversize particles. Because of the consistency test equipment requirements and differences in the nature of RCD design and construction, this method is not widely used in proportioning RCC mixtures outside of Japan [3].

2.4.2.3 Corps of Engineers Method

This method is based on experience with mix designs for seven RCC projects and is described in engineering manual 1110-2-2006 [7]. It basically follows ACI Standard 211.3R, "Standard Practice for Selecting Proportions for No-Slump Concrete" [25]. Both methods calculate mixture quantities from solid volume determinations, as used in proportioning most conventional concrete. The w/cm and equivalent cement content are established from figures based on the strength criteria using Fig. 2.6 and Fig. 2.7 [3].

The approximate water demand is based on nominal maximum size aggregate and desired modified Vebe time. A recommended fine aggregate content as a percentage of the total aggregate volume is based on the nominal maximum size and nature of the coarse aggregate. Once the volume of each ingredient is calculated, a comparison of the mortar content to recommended values can be made to check the proportions. This method also provides several unique aspects, including ideal combined coarse aggregate gradings and fine aggregate gradings limits incorporating a higher percentage of fine sizes than permitted by ASTM C 33. Because design strength for many RCC dams is based on 1 year, a target 90- or 180-days strength may be estimated using Fig. 2.6 and Fig. 2.7 [3].

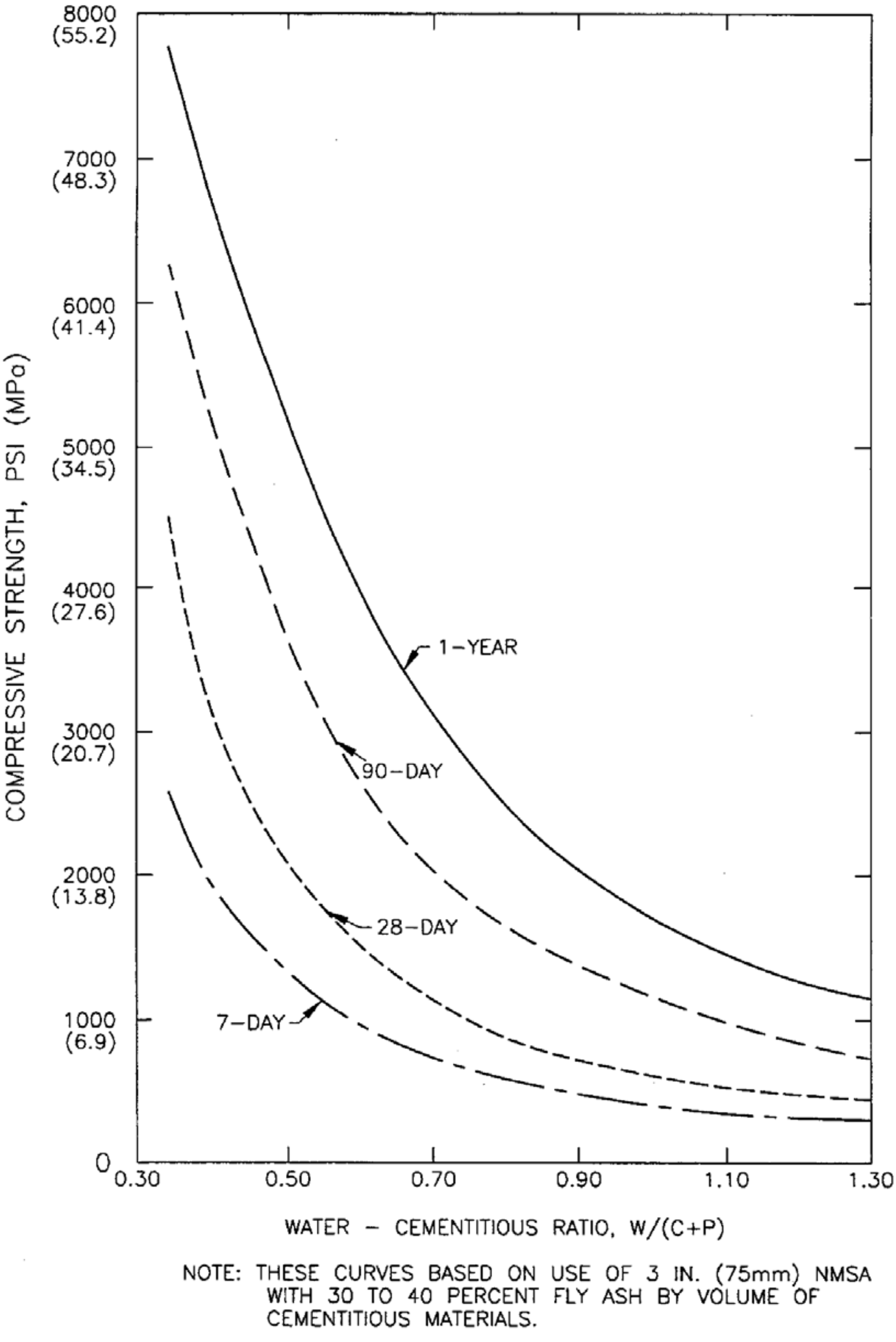


Figure 2.6 Relationship between compressive strength and w/cm [3]

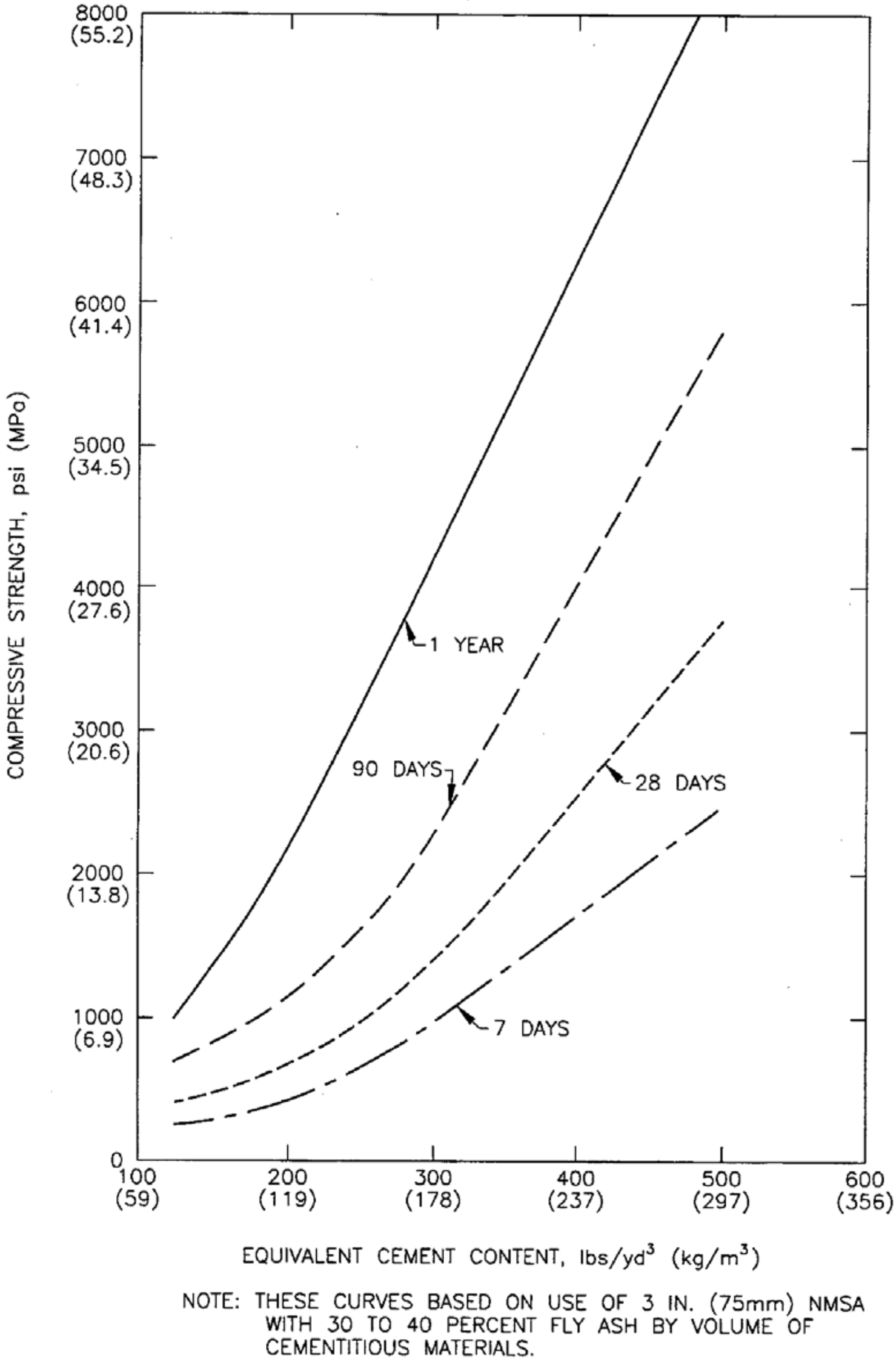


Figure 2.7 Relationship between equivalent cement content and compressive strength [3]

2.5 Advantages and Disadvantages of RCC over Conventional Mass Concrete

RCC is designed to meet the material strength and durability requirements established by the structural engineer. The factors that affect the properties of conventional mass concrete such as water-cement ratio, quality of mixing ingredients, and degree of consolidation and curing, also affect the material properties of RCC. The principal difference in the two is the mixture consistency and the method of consolidation. Internal consolidation using immersion type vibrators is used for conventional concrete, while external consolidation with spreading equipment and vibratory rollers is used for RCC. The controls placed on mixture ingredient selection for conventional mass concrete will apply to RCC. RCC mixture proportioning procedures are similar to conventional concrete; however, RCC mixtures will normally contain less water and paste and more sand to limit segregation [15].

The advantages of RCC in dam construction can be summarized as:

- More rapid construction (2.5 to 3 m vertical progress per week can be achieved in large dams, greater rates have been achieved in smaller dams);
- Effective use of conventional equipment (trucks, dozers, vibratory rollers);
- A reduced cost of construction as a consequence of the above;
- Thinner layers which lead to increased safety during construction by reducing the differences in levels between placement
- Enhanced safety by the reduced dependence on formwork;

Although well designed RCC dams are frequently the lowest cost solution when compared to other types of dams, there are conditions that can make RCC dams more expensive. Situations where RCC may not be appropriate includes when aggregate material is not readily available and construction during heavy rains or hot weather.

2.6 Bedding Mix

As RCC dams are constructed in a series of compacted lifts, bonding of the successive lifts are important. A mortar bedding mix is designed to fill the surface voids in both the compacted lift below and the covering layer above as well as to “glue” the two RCC layers together.

There are two forms of bedding mix; mortar and bedding concrete (with a maximum size of aggregate greater than 5 mm). Those dams that had used a bedding mix, approximately 77% have used mortar and 23% bedding concrete according to 97 RCC dams that were completed or under construction at the end of 1996 [2]. Bedding mortar was first used in an RCC dam at Shimajigawa Dam and all RCD dams since that time have used bedding mortars.

2.6.1 Properties of Bedding Mix

A bedding mortar or bedding concrete over the upstream zone of each lift joint is recommended for providing watertightness for any dam that will impound water for extended periods. The application of bedding mortar over the full lift surface may be necessary for dams where appreciable bond strength between lifts is necessary (such as those built in earthquake zones where more tensile and shear strength across the lift joints is required than is available without bedding mortar). Tests show that the use of a bedding mortar for low cementitious materials content mixtures can significantly increase the tensile strength and cohesion value at the joints when compared with lift joints using no bedding mortar. The need for a bedding mortar or bedding concrete for other structures such as massive foundations, dam facings, sills, and cofferdams should be based on the need for a specific level of bond or watertightness, or both [7].

The applied bedding mortar is generally 10 to maximum 0.5 inch thick. The thickness of the bedding concrete varies considerably up to 75 mm thick bedding concretes have also been applied. If the thickness of a bedding mix is too high, there can be difficulty with the compaction of the overlying RCC due to sideways of the more workable concrete. Moreover, it is difficult to balance the need for a minimum thickness for the maximum size of aggregate and the requirement for minimizing the thickness for cost and heat of hydration considerations. When using a bedding concrete (and to a lesser extent mortar), the implications of the cost and potential heat generation could be carefully considered. The cost of applying a bedding mix of whatever form, can be significant [2].

For small RCC dam projects, the mortar is usually mixed in transit mixed concrete trucks, allowed to flow onto the RCC surface and then spread by brooms, rakes or lutes.

Generally, soils approach designers specify joint treatment and the use of bedding mixes on the basis of a “Maturity Factor”; in the USA this is in “deg.F-hr” but in the rest of the world “deg.C-hr” is used (generally using ambient temperatures as the temperature factor). It is the product of the surface temperature and time of exposure until the next lift is placed. Unfortunately, there is no direct correlation. There seems to be no consensus of opinion regarding the limits for the Maturity Factor. This is probably because the conditions are so site-specific and each dam has to be considered as a unique set of conditions. The limits for Maturity Factor, if used, will be dependent upon many factors such as: the mixture (water content, quantity of paste, type of cementitious material, retardation, etc.), the workability, the potential for segregation, the compaction methods and equipment, the effectiveness of the curing, etc [2].

In order to be effective as a bonding agent between successive lifts, the mortar bedding needs to be stronger than the RCC itself. In simple terms, the "glue" needs to be stronger than the materials being glued or bonded together [26].

According to ICOLD; designers have found it prudent to define three classes of joint treatments [2]:

- *A fresh (or "hot") joint*: This is a joint that occurs when the RCC layers are being placed in rapid succession and the RCC is still workable when the next layer is placed,

- *An intermediate (or "warm" or "prepared") joint:* This is the condition that occurs between a fresh joint and a true "cold" joint,

- *A cold joint:* At this stage the surface of the previously placed layer is judged to be such that little or no penetration of the aggregate from the new layer will be possible into the previously compacted layer.

ICOLD recommends nothing for fresh joint, bedding mix treatment for intermediate joint if it is lean RCC and likewise bedding mix treatment for cold joint if it is lean, medium or high paste RCC.

Bedding mortar should be placed in a zone approximately 10 to 20 m wide in front of the area where the RCC is being spread. Application of the bedding mortar should precede placement of the RCC, usually by 10 to 15 min. The interval between spreading of the bedding mortar and placement of the RCC should be shortened during hot weather and may be extended during cold weather [7].

The results of Capanda (in Angola) and Jordao (in Brazil) Dams have showed that; use of a layer of bedding mix immediately before placing the new RCC layer improved the bond of joint in about 40%, to almost that of RCC itself, regardless of the time interval between layers.

Pacelli et al. discussed the treatment of joints in conventional concrete and RCC dams. They found that mortar bedding improved lift joint bond strength [27].

Hess concluded the following after evaluating the past and USACE studies [28]:

- Lift bedding generally increases lift joint strength for RCC, but as the mortar content of RCC increases, the benefit of the lift bedding decreases;

- Lift bedding may increase cohesion and likely has no effect on friction angle;

Xiaobin researched the effect of some bedding materials on RCC lift joint strength and found the following [29]:

- There are two weak bonding faces in the RCC lift joint treated by bedding materials, and they are entirely different;

- Bedding the RCC lift joints with ordinary cement mortar can enhance their bonding strength, but can not improve their impermeability;

- When the exposure time of RCC lift joint surface is relatively short, such as 7.5 hours, the weakest bonding face of the joint bedded by ordinary cement mortar lies between the mortar and the coarse aggregates of upper layer RCC embedded into it. In the construction field, if coarse aggregate segregation occurs on the lift joint surface and/or the w/c ratio of the bedding mortar is not controlled well, a low bonding strength is likely to be developed. Thus, bedding the RCC lift joints with ordinary cement mortar may be a good treatment, but still needs to be improved;

- Bedding the lift joints with silica fume cement mortar can enhance not only their bonding strength, but also their impermeability. The silica fume cement mortar can bond tightly with the lower layer RCC, and moreover, it can also improve the bonding strength with the coarse aggregates of upper layer RCC embedded into it due to the strong interface effect of silica fume. Silica fume cement mortar is much better than ordinary cement mortar as a bedding material;

- Bedding the RCC lift joint surface with expanding mortar may not be a good treatment.

2.6.2 Materials

According to PCA design manual for small RCC dams, a bedding mortar, consisting of portland cement, sand water, and usually a retarding admixture, should generally be proportioned to meet the following guidelines [26]:

▪ Slump	*150 to 230 mm*
▪ Maximum size of aggregate	*6 to 9.5 mm*
▪ Minimum Cement Content	*296 kg/m^3*
▪ Minus #200 sieve material	*3% maximum*
▪ Admixture; ASTM C 494, Type D water reducing & retarding	*retard initial set to greater than 3 hrs at 35°C*
▪ Design strength	*minimum 13.8 MPa at 7 days or minimum 17.2 MPa at 28 days*

For bedding concrete, US Army Corps of Engineers recommends mixture having up to 19.0 mm NMSA proportioned to have a slump of 130 to 180 mm. Bedding concrete is spread, usually by manual labor, to a thickness of 25 to 50 mm in a zone along the upstream face of the dam. The width of application ranges from several feet to approximately one-third of the width of the dam [7].

Testing of various bedding materials has shown that the use of bedding concrete incorporating coarse aggregate provides slightly better shear performance on lift joints than on similar joints bonded using a bedding mortar with no coarse aggregate [29].

2.7 Beydağ Dam RCC Studies

Beydağ Dam RCC mixture was taken as model for the preparation of laboratory-made RCC specimens. Therefore, Beydağ Dam RCC studies are given below in detail.

Beydağ Dam (located in Beydağ district of İzmir) is a RCC Dam with a large free flow spillway over the dam body, as can be seen in Figure 2.8 and Figure 2.9. The aim of the project is irrigation of an area of 22 000 hectares in Ödemiş Plain. The basic design was developed by Temelsu Inc. and also the construction designs are being done by Temelsu Inc., which designed Cindere RCC Dam. The contractor of the Beydağ Project is Özaltın Inc.

The Beydağ Project was given a start in April 2005, by performing the excavation of the alluvium zone between the two cofferdams, to reach the foundation. A construction period of 30 months for the RCC dam is being adopted, preliminarily, accordingly with the construction plan.

Characteristics of the project are summarized below:

Employer:	DSİ
Designer:	Temelsu Inc.
Contractor:	Özaltın Inc.
Location:	İzmir
River:	Küçük Menderes
Dam Type:	Roller Compacted Concrete
Aim of the Project:	Irrigation
Dam Body Volume:	2 700 000 m^3 (RCC)
Reservoir Volume:	300 hm^3
Height above Foundation:	100 m
Height above Thalweg:	60 m
Crest Length:	785 m
Spillway Design Flow:	1275 m^3/s

a) Downstream

b) Upstream

Figure 2.8 General view of Beydağ Dam

In order to determine the mixture proportions of RCC, 156 different RCC mixes were prepared and tested with various cementitious materials and different amounts [30].

The required compressive strength was specified as 7.5 MPa for 180 days in structural analysis. But the target compressive strength for laboratory studies was selected to be 15% higher to be on the safe side due to prospective construction differences.

Therefore the target compressive strength of the RCC mix was determined as:

7.5 MPa x 1.15 = 8.6 MPa at 180 days

The mix design calculation of RCC is made by the same concept of conventional concretes. But the amount of cement, fly ash and water in the mix are selected by previous design experiences. Determination of mix design is based on mix efficiency method.

Because of the suitability of the aggregate grading obtained from site all-in aggregates were used in RCC batching and the specific gravity of the all-in aggregates are calculated regarding to specific gravity of the coarse and fine aggregate including the total aggregate and the ratios of the both aggregate sizes. The concept of the calculation is given as;

$$G_{ag} = \frac{G_{coarse} \times Y_{coarse} + G_{fine} \times Y_{fine}}{100}$$

G_{ag} : Aggregate specific gravity
G_{coarse} : Coarse aggregate specific gravity
G_{fine} : Fine aggregate specific gravity
Y_{coarse} : The ratio of coarse aggregate (42%)
Y_{fine} : The ratio of fine aggregate (58%)

The evaluations of the required cementitious material content were selected based on Cindere Dam mix design studies which show similar properties with Beydağ Dam. In Cindere Dam, target strength was achieved with 50 kg/m^3 cement and 20 kg/m^3 fly ash after the trial studies, the fly ash ratio being 30% of the total cementitious material. In Beydağ aggregates, the content passing the No. 200 sieve is lower than Cindere Dam aggregates therefore in Beydağ trials, the fly ash content is increased approximately 15%.

The target compressive strength of RCC is mentioned around 7.5 MPa for 180 days in previous structural studies. But the trial mixes were designed up to 15 MPa compressive strength for one year. The required cementitious material contents are determined according to Cindere Dam trial studies. Cementitious material range is;

7 (MPa) / 0.113 (*) (MPa / (kg/m^3)) = 62 kg/m^3 and
15 (MPa) / 0.113 (*) (MPa / (kg/m^3)) = 132 kg/m^3
(*) Mix efficiency value of Cindere Dam mixes with 50% percent fly ash content

Finally, the cementitious content of the mixes was determined between 60 kg and 150 kg per cubic meter of RCC. The fly ash ratio is fixed between 30% and 50%. The Yatağan fly ash has been used for trial mixes which is the closest source to the job site.

The Beydağ mixes were designed with minimum water content to show target compaction value. In general, concept behind RCC Vebe time is the criteria of workability but, like Beydağ Dam, low cementitious content mixes can not be evaluated with Vebe time. Therefore the Vebe time was kept above 50 seconds for Beydağ mixes and maximum compaction ratios observed by trials. Finally the water content was kept between 115 lt/m^3 and 130 lt/m^3. The objective of the reduction of water content was to achieve maximum strength with minimum cement content.

Then, 156 different mixes were tried to achieve required compressive strength. Firstly, the water content of the aggregate was determined and regarding the absorption, water corrections were made. 100 lt mix was prepared in laboratory mixer. Gradation, water content and compacted unit weight tests were performed on the samples. The mix, placed in Ø 15 x 30 cm cylinder moulds with compressed air gun in three layers. Each layer was compacted for up to 15 seconds in order to reach minimum 98% compaction.

During the trial mix study 63 mixes and 888 cylinders were prepared with separated aggregate fractions and 93 mixes and 1293 cylinders were prepared with continuous 0-50 mm aggregate. In total, 156 mixes and 2181 cylinders were prepared. 24 hours later, the samples were taken from moulds and put in 23 ± 2 °C water tank up to testing date.

In preliminary studies, two kinds of aggregate have been tried and the effect of aggregate properties on strength have been investigated. Eventually, 0-50 mm continuous aggregate type was selected and the mixes were prepared with that type of aggregate afterwards. After selection of aggregate type, different cement and fly ash sources were also tried in trial mixes.

At first, an electric kango hammer was used for compaction of the cylinders. However, required compaction could not be achieved therefore low compressive strength results were obtained. After evaluation of those results, the equipment was changed with compressed air gun for compaction of the cylinders.

As a result of all studies expressed above, 7 mixes which show strength values close to the design strength at 180 days are given in Table 2.3.

If the assumed results are evaluated, it can be seen that all selected mixes achieved the required target compressive strength except BB-2 and BB-5.

The water contents of the mixes changed between 110 lt and 125 lt and the water content directly affects the compressive strengths. Anyhow the mixes BBK-1A and BBK-3A achieved required strength with 110 lt/m^3 of water but BB-2 and BB-5 mixes could not achieve required target compressive strength with same cementitious content and 125 lt water per m^3. Generally all around the world water content of the RCC mixes kept over 125 lt/m^3, as Cindere Dam.

Table 2.3 Beydağ Dam trial mixes [30]

Mix ID	Content	Compressive Strength (MPa)				
		7 Days	28 Days	56 Days	90 Days	180 Days
BB-2	50 C (Denizli***)+40 F+125W	3.6	4.5	5.5	5.8	7.4*
BB-5	50 C (Batıçim***)+40 F+125W	3.3	4.3	5.1	6.1	7.4*
BBK-1A	50 C (Denizli***)+40 F+115W	3.8	4.9	5.9	7.4	8.7**
BBK-3A	50 C (Denizli***)+40 F+115W	3.6	4.8	5.9	7.4	8.5**
BBK-4A	50 C (Çimentaş***)+40 F+110W	5.0	5.9	6.6	8.0	10.2**
BBK-9	60 C (Denizli***)+30 F+125W	4.4	5.3	5.8	6.8	8.9**
BBK-10	60 C (Denizli***)+40 F+110W	5.8	7.8	8.2	9.4	12.4**

* Achieved result by trial mix study
** Assumed strengths obtained by Mix Efficiency Factor
*** Cement Manufacturer

If the effect of water on compaction is taken into consideration, the samples can be compacted with lower water content in the laboratory conditions but regarding the site conditions it could be very difficult. Any increment of water on site without increasing of the cementitious material will reduce strength directly and it will be very undesirable. The initiation of the RCC placement will be in summer so this risk should be considered. Therefore, 125 lt water per cubic meter for RCC were used without taking any risk.

Finally, BBK-9 with 60 kg/m^3 cement, 30 kg/m^3 fly ash and 125 lt/m^3 water was selected for the proper RCC mix design. Unit weight of saturated surface dry RCC is 2376 kg/m^3.

For the RCC joint treatment, bedding mortar is suggested between old and freshly placed RCC layer if the time interval between layers exceeds 24 hours. The proper bedding mix should be stronger than RCC. For this reason, in the mix 350 kg/m^3 cement and 350 lt/m^3 water were used. As aggregate 7 mm NMSA was used. In the mix admixture were not used. The prepared mix shows strength value of about 10-11 MPa at 180 days which is almost 25% more than that of RCC.

2.8 Previous Research at M.E.T.U.

As a first study, in his M.S. Thesis, Eyüp Sabri Koçak investigated the most economical and suitable materials to be used in Suçatı Dam in Kahramanmaraş. In that study, two types of ordinary portland cement, one type of fly ash, one type of ground granulated blast furnace slag, various portland cement-fly ash and portland cement-slag combinations, and aggregates taken from six different sources in the region were used in producing the RCC mixtures. As a result of the experimental study, it was found that using slag in RCC as cementitious material was more economical than using fly ash. Moreover, the optimum cementitious material content for RCC was determined to be 125-150 kg/m^3, 100-125 kg/m^3 of which was ground granulated blast furnace slag reducing the cement content by an amount of 90% [31].

In another study, as a M.S. Thesis, Özlem Aslan studied the long term strength prediction of RCC containing natural pozzolan by steam curing. The aim of the project was to obtain the optimum RCC mixture to generate compressive strength of 7 MPa in the long term at project site, Akköy-I Dam and hydroelectric power plant construction. In this thesis, two types of cement, two types of natural pozzolan, aggregates with varying gradations, and a type of water reducing chemical admixture were used. Additionally, steam curing was applied to the test specimens in order to get long term compressive strength at early ages. Differences between steam cured specimens and normal cured specimens were discussed. It was observed that application of steam curing in CEM I type cement used RCC mixtures generated expected results. However, in CEM IV type cement used RCC mixtures compressive strength results did not behave in the same manner. Also, it was shown that usage of water reducing chemical admixture improved compressive strength of RCC [32].

Moreover, Salah Eddin Sabri investigated the bond strength testing between two different materials which was a Ph.D. Thesis made at M.E.T.U. Materials of Construction Laboratory. He investigated the theoretical and experimental bond between two materials. In the study, it was found that splitting tensile test, which was originally used to measure the splitting tensile strength of stones and concrete, can be applicable to measure the bond strength between two materials experimentally. The results of that study proposes a formula which was derived using finite element method, that gives accurate bond strength values. Moreover, for most of the material combinations this method was shown to be reproducible with a coefficient of variation less than 13%. Mode of failure is found to be always at the interface [33].

Lastly, Raci Bayer in his M.S. Thesis, studied the use of preplaced aggregate concrete (PAC) for mass concrete applications. In that research, a new method for making PAC was investigated. The new method was based on increasing the fluidity of the grout by new generation superplasticizers to such an extent that, it filled all the voids in the preplaced coarse aggregate mass when it was simply poured over the aggregate mass, without requiring any injection. As a result of the experimental study it was found that, the PAC specimens prepared by injection method performed better in terms of thermal properties, but was worse in mechanical properties than conventional concrete. On the other hand, the PAC specimens prepared by the new method performed beter when compared to PAC and concrete [34].

CHAPTER 3

EXPERIMENTAL STUDY

In the experimental study, RCC used in Beydağ Dam whose construction is still underway, was taken as model and the studies were prosecuted. Beydağ Dam RCC was evaluated to be lean RCC with 90 kg/m^3 cementitious content (60 kg/m^3 cement + 30 kg/m^3 fly ash).

As previously explained in Section 2.6, bedding mix is often used for RCC in between freshly placed and previously compacted layer. However, there is not enough research about the timing of bedding mix application. Consequently, the aim of the study was to investigate the properties of RCC with and without bedding mix as a bonding agent between successive layers.

However, around the world there are no clear experimental standards for some properties (permeability, coefficient of internal friction) of RCC, so CVC standards are used instead.

Good compaction is vital for RCC. In the experiments, a Spit 490 electro pneumatic demolition hammer was used for compaction whose detailed properties are given in the following sections.

Moreover, in the continuing sections constituents for RCC and bedding mix, the preparation of specimens, the specimen notation used in the thesis and the curing procedure were provided.

3.1 Materials Utilized within the Experimental Program

The materials to be used in the study constitute aggregates from Küçük Menderes water course, CEM I 42.5 R Portland Cement from Set Çimento, fly ash from

Seyitömer Thermal Power Plant and local fine aggregate obtained from Ankara to be used in the bedding mix. In the continuing sections the properties of each ingredient are given in detail.

3.1.1 Cement

Portland cement which was obtained from Set Cement Factory was used for RCC and bedding mix, and it is classified as CEM I 42.5 R according to Turkish Standards (similar to Type I - Ordinary Portland Cement according to ASTM C 150 classification). Chemical analysis and the physical properties of this cement along with ASTM C150 [16] limitations are given in Table 3.1 and Table 3.2 respectively.

Table 3.1 Chemical analysis of Portland Cement

Oxides and Other Properties	**% by weight**	**ASTM Limit (C150)**
CaO	62.51	-
SiO_2	19.62	-
Al_2O_3	5.22	-
Fe_2O_3	3.51	-
MgO	1.79	max. 6.0%
SO_3	2.83	max. 3.0%
K_2O	0.70	-
Na_2O	0.24	-
P_2O_5	0.05	-
TiO_2	0.28	-
Cr_2O_3	0.09	-
Mn_2O_3	0.06	-
Free CaO	-	max. 3.0%
Cl^-	-	max. 0.1%
Loss on Ignition	2.30	max. 3.0%
Insoluble Residue	0.50	max. 0.75%

Table 3.2 Physical properties of Portland Cement

Property		Value	ASTM Limit (C150)
Specific Gravity		3.11	-
Blaine Fineness (cm^2 /g)		3361	min. 2800
Compressive Strength (MPa)	2 days	23.6	-
	7 days	36.6	min. 19.00
	28 days	51.9	-

3.1.2 Fly Ash

Fly ash which is obtained from Seyitömer Thermal Power Plant was utilized in this study (similar to Class F fly ash according to ASTM C 618 [19] classification). Chemical analysis and the physical properties of this fly ash are given in Table 3.3 and Table 3.4 respectively.

Table 3.3 Chemical analysis of fly ash

Oxides and Other Properties	% by weight	ASTM Limit (C 618)
CaO	3.13	-
SiO_2	56.56	-
Al_2O_3	18.75	-
Fe_2O_3	11.08	-
MgO	4.61	-
SO_3	0.76	max. 5.0%
K_2O	1.71	-
Na_2O	0.10	max. 1.5%
P_2O_5	0.11	-
TiO_2	1.06	-
Cr_2O_3	0.10	-
Mn_2O_3	0.23	-
Loss on Ignition	0.90	max. 6.0%

Table 3.4 Physical properties of fly ash

Property		Value	ASTM Limit (C 618)
Specific Gravity		2.26	-
Blaine Fineness (cm^2 /g)		3215	-
Strength Activity Index (%)	7 days	69	min. 75%
	28 days	83	min. 75%

3.1.3 Aggregate for RCC

The aggregate used for RCC preparation was brought from the water course of Küçük Menderes River (Figure 3.1) It was taken 2 km downstream of Beydağ Dam body.

Figure 3.1 A view of aggregates brought from Küçük Menderes River

Nominal maximum aggregate size is determined in the laboratory as 50 mm. As previously mentioned in section 2.7, material under 50 mm NMSA is quite uniform. Therefore, in the mix design studies of Beydağ Dam, it was accepted to use continuous graded 0-50 mm aggregate instead of using fraction of aggregates. The combined gradation curve of the used aggregate is given in Figure 3.2 which conforms to relevant standard ACI 207.5R-89 [1]. Specific gravity and absorption tests were also performed following the ASTM C 127 [35] and C 128 [36] standards and the results are presented in Table 3.5.

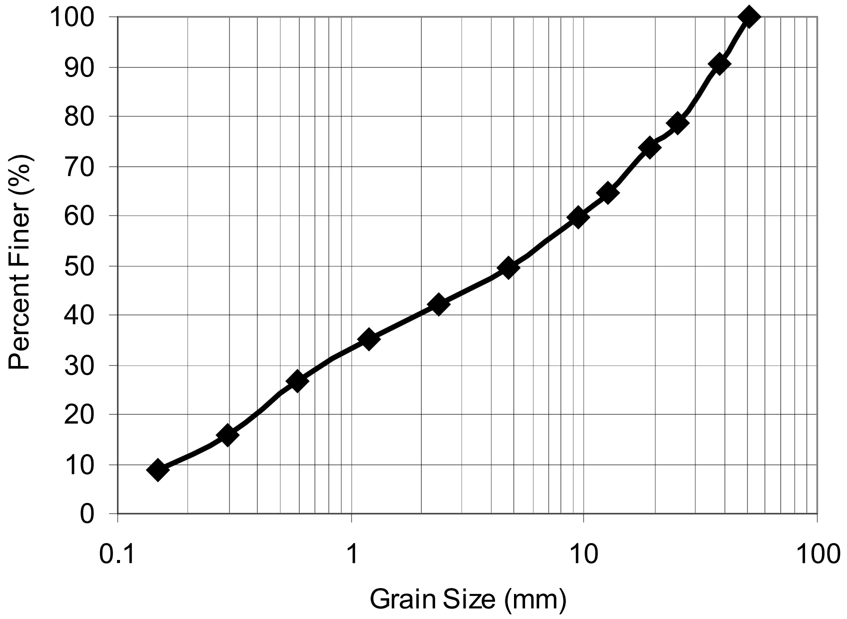


Figure 3.2 Combined gradation curve of aggregate used in RCC

Table 3.5 Physical properties of aggregate used for RCC

Property		**Combined Aggregate**
Specific Gravity	Dry	2.52
	SSD	2.58
Absorption (%)		2.76
Passing No. 200 sieve (%)		3.57

3.1.4 Aggregate for Bedding Mixes

The aggregate used for bedding mixes consist of fine particles with 4.76 mm NMSA. It was obtained from local sources. Physical properties and gradation curve for aggregate is given in Table 3.6 and Figure 3.3, respectively.

Table 3.6 Physical properties of aggregate used for bedding mixes

Property		**Fine Aggregate**
Specific Gravity	Dry	2.49
	SSD	2.56
Absorption (%)		2.65
Passing No. 200 sieve (%)		3.32

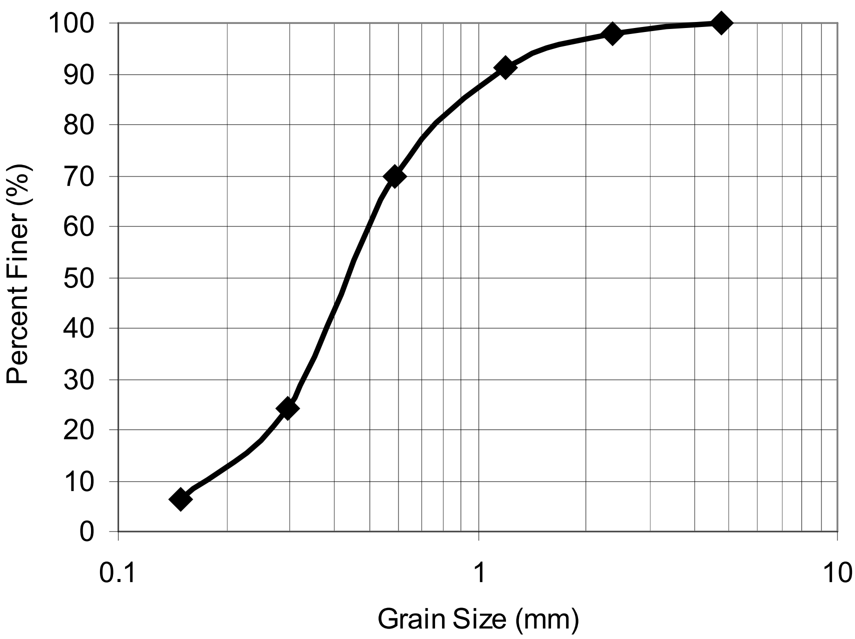


Figure 3.3 Gradation curve of aggregate used for bedding mixes

3.2 Experimental Program

The proportion of the materials used in the RCC mix is same as Beydağ Dam mix design. The RCC mix consists of 60 kg/m^3 cement, 30 kg/m^3 fly ash, 125 lt/m^3 water and 2161 kg/m^3 aggregate. However, water correction was made in the mix due to water content of aggregate in the mixing days. So, 10 mixes have been prepared depending on moisture content of aggregate.

For the bedding mixes used between different layers of RCC, a mortar is selected as far as Beydağ Dam bedding mortar is considered. However, two different bedding mortars are used in the study. One of them is a poor mix with 200 kg/m^3 cement and 400 lt/m^3 water while other is rich mix with 400 kg/m^3 cement and 400 lt/m^3 water. The selected cement contents are compatible with minimum cement content given in PCA design manual for small RCC dams [26] which is 296 kg/m^3. The given minimum cement content value is in between cement contents of poor and rich bedding mixes. The water content of the rich mix is selected by mix observations and previous bedding mix data whereas the water content of the poor mix is selected by flow test (ASTM C 1437 [39]). In the test the flow diameter of the rich mix is increased to 21 cm. Then the water content of the poor mix is adjusted to show flow diameter of 21 cm. It is found that 400 lt/m^3 is the design water content of the poor mix with same flow.

Poor and rich bedding mortars are designated as B-1 and B-2 respectively. SSD mix proportion for B-1 is 200 kg/m^3 cement, 400 lt/m^3 water and 1373 kg/m^3 aggregate while B-2 mix consists of 400 kg/m^3 cement, 400 lt/m^3 water and 1211 kg/m^3 aggregate. Same as RCC mixture, water correction was made for B-1 and B-2. So, there are 10 mix compositions for each of the bedding mortars due to water correction.

Using the RCC and bedding mixture proportions described above an experimental program is designed by changing the application time of different bedding mixes.

Time interval between layers and applied bedding mortar types are the cases formed the notation. In the thesis the notation given in Table 3.7 is used for the specimens.

When labeling the mixes presented in the first column of Table 3.7 the first number at the left of B shows the time interval (hours) between layers. In this experimental study this time interval of application of the bedding mixes was changed from 0 to 16 hours at 4 hours intervals. The first number at the right of B shows the applied bedding mortar type: “0” stands for no bedding, “1” for poor and “2” for rich bedding mix.

Table 3.7 Specimen notation used in the experiments

Mix ID	**Time interval between layers (hours)**	**Applied bedding mortar type**
0-B-0	0	No bedding
0-B-1		Poor bedding mix
0-B-2		Rich bedding mix
4-B-0	4	No bedding
4-B-1		Poor bedding mix
4-B-2		Rich bedding mix
8-B-0	8	No bedding
8-B-1		Poor bedding mix
8-B-2		Rich bedding mix
12-B-0	12	No bedding
12-B-1		Poor bedding mix
12-B-2		Rich bedding mix
16-B-0	16	No bedding
16-B-1		Poor bedding mix
16-B-2		Rich bedding mix

Each specimen that was prepared was also labeled by a number following the mix ID, taking any value between 1 to 16. Each specimen was used for a different test. 1 to 3 and 9 to 11 show 28-days and 90-days compressive strengths, respectively. Whereas, 4 to 6 and 12 to 14 show 28-days and 90-days splitting tensile strengths. Finally, 7-8 and 15-16 show 28-days and 90-days permeability test specimens, respectively.

Compaction

During the construction of RCC mixtures in the laboratory, one of the most important parameters is compaction. All of the RCC properties depends on compaction. As a result of proper compaction, fully compacted RCC specimens will be formed. In the study, an electro pneumatic demolition hammer type (Spit 490) is preferred for compaction equipment (Figure 3.4) because of conformance of impact rate, impact force, weight and minimum power input with ASTM C 1435 [8] standard. It is an electro pneumatic demolition hammer with adjustable impact force through 6 levels.

Figure 3.4 A view of the compaction equipment

The properties of the electro pneumatic demolition hammer is given below:

- Weight : 10.1 kg
- Power input : 1500 W
- Power output : 1000 W
- Impact rate : 950-2090 blows per minute
- Impact force : (Max) 6-25 Joule
- Tool holder : SDS Max
- Chisel positions : 12
- Noise : Below 108 decibel
- Vibration : Weighted acceleration below 13 m/s^2

Specimen Preparation

Before mixing, the water content of the aggregate is determined and regarding this water corrections were made. Then, materials to be added to the mix is weighed separately. After weighing all the materials, they were placed inside the electrical mixer (Figure 3.5). Until all the water is absorbed by the materials, the materials are mixed in the mixer. Later, the moulds are filled with the help of a shovel as shown in Figure 3.6. The moulds are filled with RCC in two layers. Each layer has a height of 7.5 cm when bedding mortar is not applied and 7 cm when applied for the specimens. The RCC filled moulds are compacted with electro pneumatic demolition hammer by the help of apparatus fixed to the end of chisel (Figure 3.7). Each layer is compacted 30 seconds with the demolition hammer, which has approximately 2090 blows per minute vibration rate and 25 Joule impact force (Figure 3.8).

Figure 3.5 A view of the electrical mixer

Figure 3.6 A view of the filling of moulds with RCC

Figure 3.7 A view of the apparatus used for compaction of cubic specimens

Figure 3.8 Typical view of the compaction process

After the application of the first layer of RCC, the bedding mix and the second RCC layer was applied. In this study, different time intervals between compacted layers were selected. In Figure 3.9, the compacted first layers of specimens are shown. In this position, the specimens left for 4, 8, 12 and 16 hours until the filling and compaction of the second layer. In those cases, bedding mortar was applied at a height of 1 cm shortly before the filling of the second layer (Figure 3.10). The specimens were cured under room conditions until the test date. Specimens are covered with damp cloths that were kept wet throughout the curing period.

Figure 3.9 A view of the RCC specimens waiting for the application of the bedding mix and the second RCC layer

Figure 3.10 A view of the application of bedding mix

3.3 Experimental Procedures and Data

3.4.1 Compressive Strength

The compressive strength tests were performed according to TS 12390-3 [38] for all specimens. For each case of RCC and bedding mix combinations, 3 cubic specimens (15 x 15 x 15 cm) were subjected to compressive load until failure (Figure 3.11).

The 28-day and 90-day compressive strength test results of specimens for each combinations of RCC and bedding mixes are given in Table 3.8 and Table 3.9 respectively. In the tables, mean compressive strength and coefficient of variation of specimens are also provided in the last two columns.

a) Before test

a) After test

Figure 3.11 Typical view of specimens used in compressive strength testing

Table 3.8 28-day compressive strength test results of RCC

Mix ID	Compressive Strength (MPa)				
	Specimen No			Mean	Coefficient of Variation (%)
	#1	#2	#3		
0-B-0	5.3	5.5	4.7	***5.2***	***8.4***
0-B-1	4.8	4.5	4.5	***4.6***	***3.4***
0-B-2	5.1	5.1	3.2*	***5.1***	***0.8***
4-B-0	5.1	5.3	5.0	***5.2***	***2.7***
4-B-1	4.6	4.6	4.5	***4.6***	***1.0***
4-B-2	5.4	5.0	5.2	***5.2***	***4.4***
8-B-0	4.3	4.8	4.3	***4.5***	***6.0***
8-B-1	4.5	4.7	4.4	***4.5***	***3.0***
8-B-2	5.5	4.9	4.6	***5.0***	***8.6***
12-B-0	5.6	3.0*	4.0	***4.8***	***23.9***
12-B-1	4.7	5.3	4.8	***4.9***	***6.2***
12-B-2	4.8	5.9	5.2	***5.3***	***10.5***
16-B-0	5.0	4.3	4.7	***4.6***	***8.0***
16-B-1	5.1	4.7	4.5	***4.8***	***6.1***
16-B-2	4.9	5.4	5.0	***5.1***	***5.1***

* Disregarded due to the appearance of a big stone in the middle of the specimen

Table 3.9 90-day compressive strength test results of RCC

Mix ID	Compressive Strength (MPa)				
	Specimen No			Mean	Coefficient of Variation (%)
	#1	#2	#3		
0-B-0	9.1	9.0	9.2	***9.1***	***1.5***
0-B-1	8.6	8.2	8.4	***8.4***	***2.3***
0-B-2	10.5	10.7	10.1	***10.4***	***2.9***
4-B-0	8.2	7.2	8.1	***7.8***	***7.0***
4-B-1	8.0	8.3	7.6	***8.0***	***4.9***
4-B-2	9.1	8.8	9.1	***9.0***	***2.0***
8-B-0	7.7	7.1	7.8	***7.6***	***4.8***
8-B-1	8.3	8.2	7.4	***8.0***	***6.8***
8-B-2	9.2	8.7	8.6	***8.8***	***3.5***
12-B-0	7.3	7.1	7.7	***7.4***	***4.0***
12-B-1	6.9	8.2	8.4	***7.9***	***10.3***
12-B-2	8.8	8.9	8.0	***8.6***	***6.0***
16-B-0	6.8	7.3	6.9	***7.0***	***3.3***
16-B-1	7.7	8.1	7.2	***7.6***	***5.9***
16-B-2	8.9	8.7	8.2	***8.6***	***4.4***

Beydağ Dam RCC 90-day compressive strength test result for the selected mix design was 6.8 MPa when tested using Ø15 x 30 cm cylinder specimens. When compared, our laboratory specimens without any bedding mix had 90 days compressive strengths of 9.1 MPa. Therefore, it was concluded that the compaction effort utilized was successful.

28-day and 90-day compressive strength values show higher standard deviations therefore higher coefficient of variations. However, this is in the nature of RCC as explained in Section 2.2.3.

The 28-day and 90-day compressive strength test results of only bedding mix specimens are given in Table 3.10 and 3.11 respectively. As can be seen from the tables one of the bedding mix was weaker than RCC whereas, the other one was stronger than RCC at 28 and 90 days.

Table 3.10 28-day compressive strength test results of bedding mixes

Compressive Strength (MPa)				
Mix ID	**#1**	**#2**	**Mean**	**Coefficient of Variation (%)**
B-1	2.3	2.4	***2.3***	***3.9***
B-2	10.4	9.8	***10.1***	***4.6***

Table 3.11 90-day compressive strength test results of bedding mixes

Compressive Strength (MPa)				
Mix ID	**#1**	**#2**	**Mean**	**Coefficient of Variation (%)**
B-1	4.3	5.4	***4.8***	***16.0***
B-2	18.0	18.4	***18.2***	***1.7***

3.4.2 Splitting Tensile Strength

Splitting tensile strength of cubic specimens were determined according to TS EN 12390-6 [39] standard. Cube (15 x 15 x 15 cm) specimens were compressed with the apparatus described in the standard as seen in Figure 3.12. For each combinations of RCC and bedding mixes, 3 specimens were subjected to compressive load from the midline of the surface which is parallel to the joint.

a) During test b) After test

Figure 3.12 Typical view of specimens used in splitting tensile strength testing

The 28-day and 90-day splitting tensile strength test results of specimens for each combinations of RCC and bedding mix were given in Table 3.12 and 3.13 respectively. In the tables mean splitting tensile strength and coefficient of variation values are also provided.

Table 3.12 28-day splitting tensile strength test results of RCC

Splitting Tensile Strength (MPa)					
Mix ID	**Specimen No**			**Mean**	**Coefficient of Variation (%)**
	#1	**#2**	**#3**		
0-B-0	0.17*	0.34	0.37	***0.36***	***5.2***
0-B-1	0.30	0.19*	0.34	***0.32***	***10.0***
0-B-2	0.34	0.34	0.16*	***0.34***	***1.5***
4-B-0	0.33	0.27	0.32	***0.31***	***10.8***
4-B-1	0.35	0.37	0.36	***0.36***	***3.3***
4-B-2	0.37	0.46	0.45	***0.43***	***12.0***
8-B-0	0.18	0.17	0.23	***0.19***	***17.1***
8-B-1	0.28	0.29	0.30	***0.29***	***3.5***
8-B-2	0.42	0.35	0.40	***0.39***	***8.4***
12-B-0	0.22	0.22	0.25	***0.23***	***7.7***
12-B-1	0.33	0.37	0.33	***0.34***	***6.1***
12-B-2	0.46	0.39	0.43	***0.42***	***8.2***
16-B-0	0.28	0.21	0.25	***0.25***	***13.8***
16-B-1	0.27	0.27	0.29	***0.28***	***4.1***
16-B-2	0.36	0.36	0.33	***0.35***	***4.2***

* Disregarded due to the appearance of a big stone in the middle of the specimen

Table 3.13 90-day splitting tensile strength test results of RCC

Splitting Tensile Strength (MPa)					
Mix ID	**Specimen No**			**Mean**	**Coefficient of Variation (%)**
	#1	**#2**	**#3**		
0-B-0	0.68	0.50	0.40	***0.52***	***26.8***
0-B-1	0.55	0.58	0.32*	***0.56***	***3.6***
0-B-2	0.46*	0.74	0.75	***0.75***	***0.9***
4-B-0	0.37	0.32	0.33	***0.34***	***8.7***
4-B-1	0.48	0.42	0.51	***0.47***	***9.5***
4-B-2	0.68	0.72	0.71	***0.71***	***2.9***
8-B-0	0.31	0.29	0.25	***0.28***	***11.8***
8-B-1	0.39	0.47	0.47	***0.44***	***11.1***
8-B-2	0.56	0.71	0.73	***0.66***	***14.2***
12-B-0	0.24	0.21	0.36	***0.27***	***29.7***
12-B-1	0.41	0.48	0.63	***0.51***	***21.9***
12-B-2	0.56	0.73	0.73	***0.67***	***14.3***
16-B-0	0.25	0.24	0.22	***0.24***	***5.4***
16-B-1	0.51	0.51	0.53	***0.52***	***2.5***
16-B-2	0.65	0.68	0.69	***0.67***	***3.6***

* Disregarded due to the appearance of a big stone in the middle of the specimen

For each case of bedding mixes, 2 specimens were also subjected to splitting tensile strength test from the midline of the surface which is parallel to the joint. The 28-day and 90-day splitting tensile strength test results of specimens for each are given in Table 3.14 and 3.15 respectively.

Table 3.14 28-day splitting tensile strength test results of bedding mixes

Splitting Tensile Strength (MPa)				
Mix ID	**#1**	**#2**	**Mean**	**Coefficient of Variation (%)**
B-1	0.25	0.39	***0.32***	***30.9***
B-2	1.19	1.13	***1.16***	***3.7***

Table 3.15 90-day splitting tensile strength test results of bedding mixes

Splitting Tensile Strength (MPa)				
Mix ID	**#1**	**#2**	**Mean**	**Coefficient of Variation (%)**
B-1	0.39	0.30	***0.35***	***18.4***
B-2	1.26	1.05	***1.16***	***12.9***

3.4.3 Permeability

The water permeability of 28 days specimens were tried to be determined at State Hydraulic Works, Department of Technical Research and Quality Control (DSİ TAKK) Laboratory complying with TS 12390-8 (Figure 3.13). However, most of the specimens failed during testing due to poor structure of RCC with respect to conventional concrete. Therefore, the test method was changed to sorptivity test which is standardized by ASTM C 1585 [40] and the 90 days tests were conducted in Materials of Construction Laboratory of M.E.T.U.

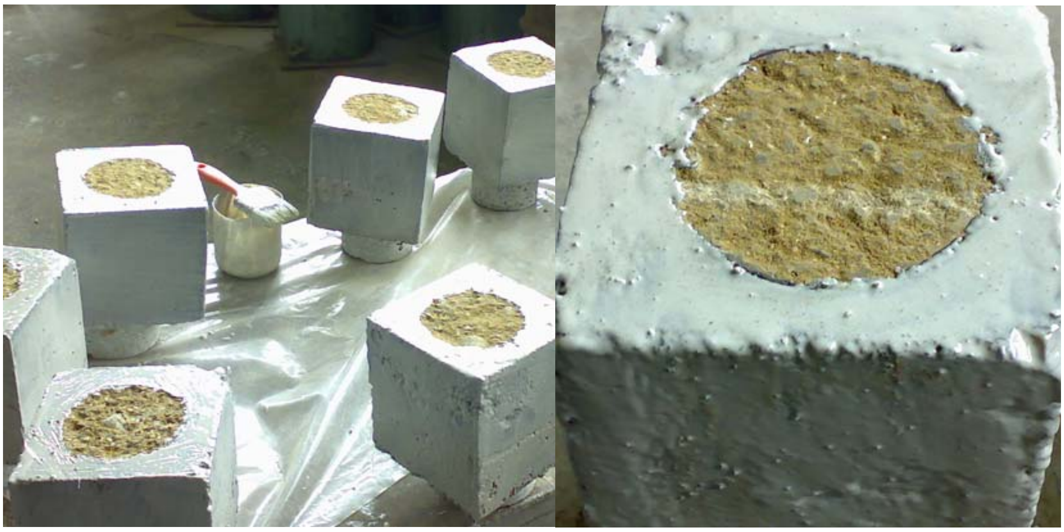


Figure 3.13 Specimens for permeability testing at DSİ TAKK

The sorptivity test method consisted of registering the increase in the mass of a prism specimen (Height: 5 cm, Diameter: 10 cm) at given intervals of time (1, 2, 3, 4, 6, 8, 12, 16, 20, 25, 36, 49, 64, 81, 120 and 360 minutes) when permitted to absorb water by capillary suction (Figure 3.14). The core specimens were taken such that the flow of water was paralel to the bedding mix as shown in Figure 3.14.

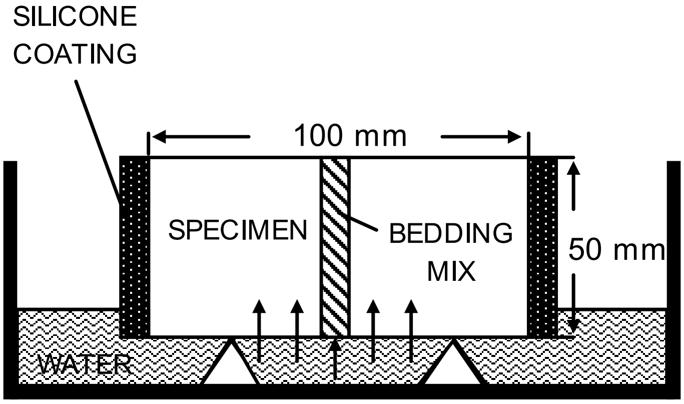
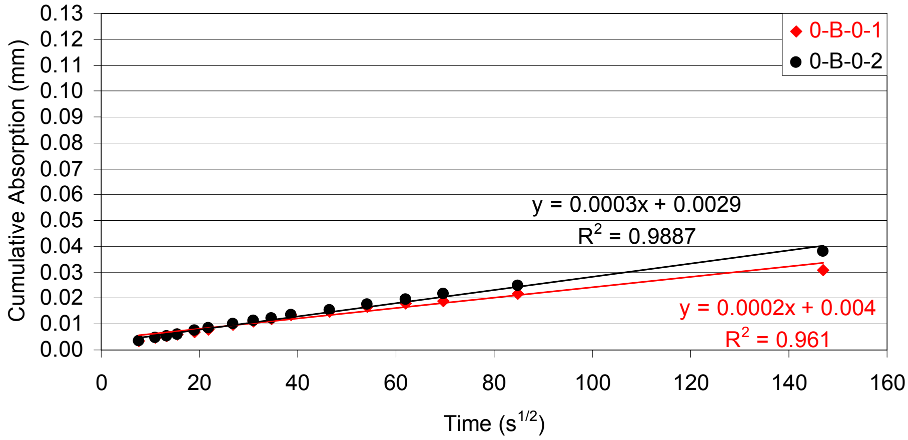


Figure 3.14 Schematic description of sorptivity test

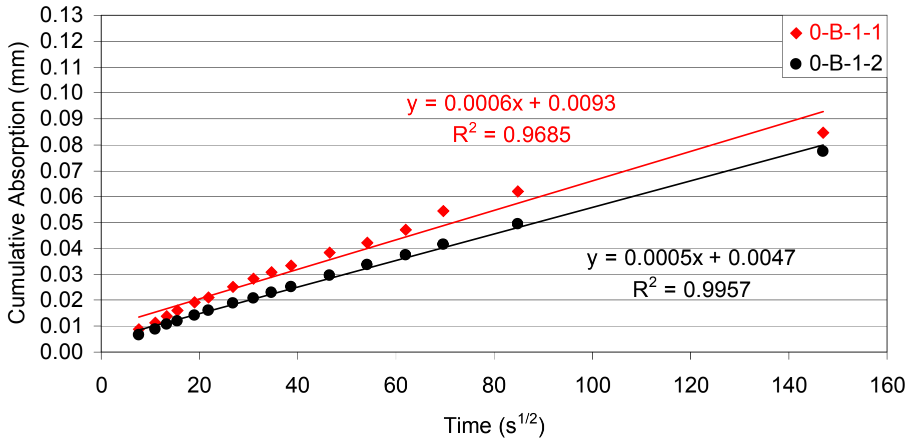
The Ø10 x 5 cm cylindrical cores are taken from 15 x 15 x 15 cm cube specimens. Then specimens were dried in an oven at 50°C for 3 days. The sides of the specimen were sealed with an epoxy in order to have one-directional flow through the specimen. Only one surface of the specimen was allowed to be in contact with water, with the depth of water between 3 to 5 mm.

The rate of absorption (mm), defined as the change in mass (g) divided by the cross-sectional area of the specimen (mm^2) and the density of water at the recorded temperature (g/mm^3), was plotted against square root of time ($sec^{1/2}$). The slope of the obtained line defines the sorptivity index (S_0) of the specimen.

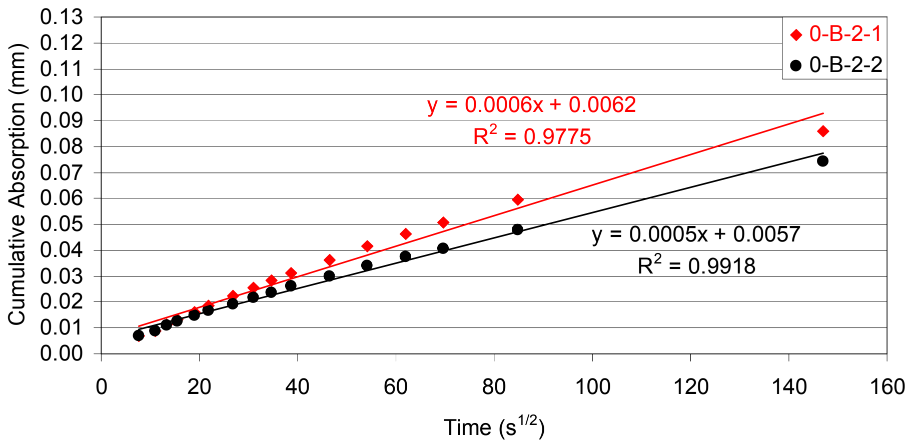
The standard states that, if the data between 1 minute and 360 minute do not follow a linear relationship (a correlation coefficient of less than 0.98) and show a systematic curvature, the initial rate of absorption cannot be determined. Then the test is continued up to 7 days. The 90 days results of combinations of RCC and bedding mix specimens are given in Figure 3.15-3.19. However, all of the correlation coefficients, R, were higher than 0.98 and therefore the test was stopped at 360 minutes.



a) No bedding

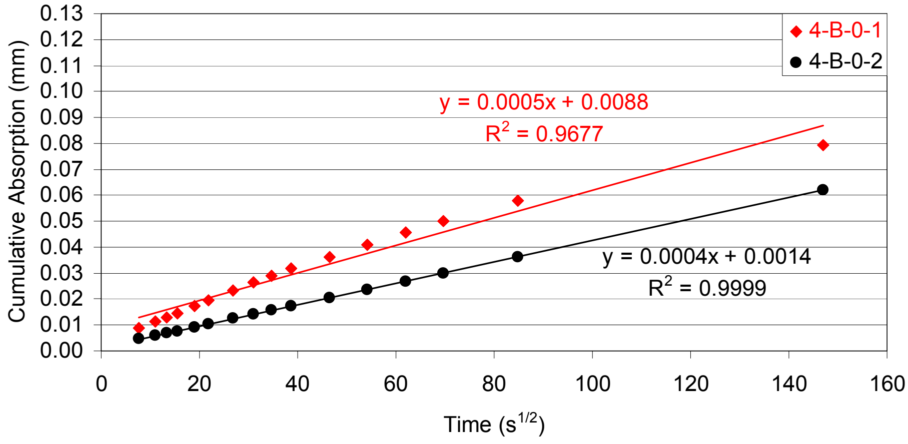


b) Poor bedding mix applied

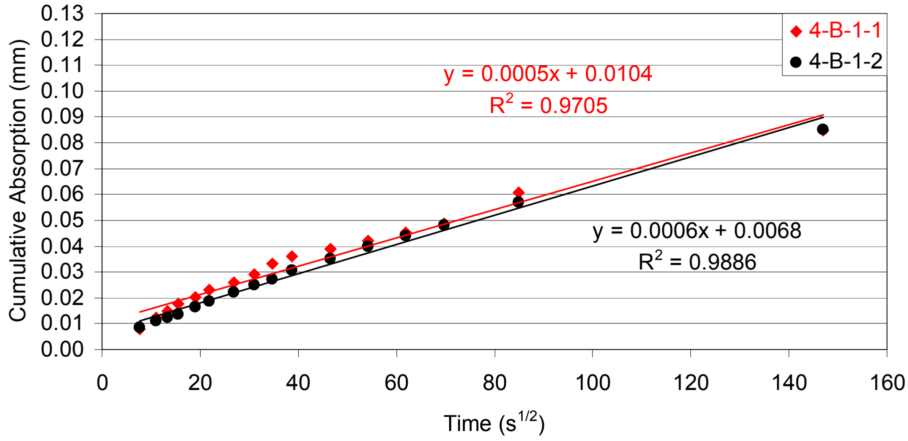


c) Rich bedding mix applied

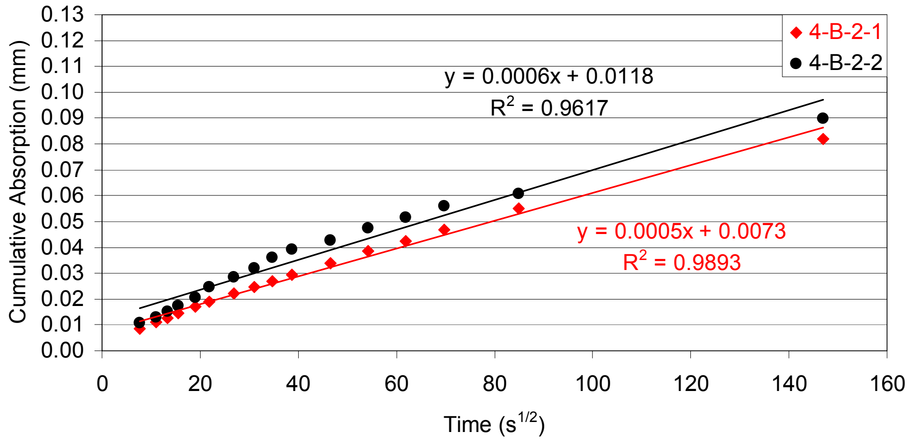
Figure 3.15 Permeability of RCC specimens with 0 hour time interval between layers



a) No bedding

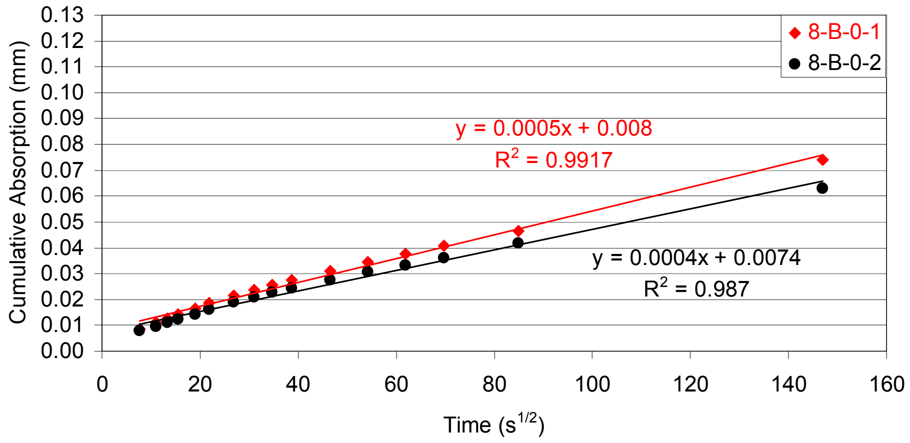


b) Poor bedding mix applied

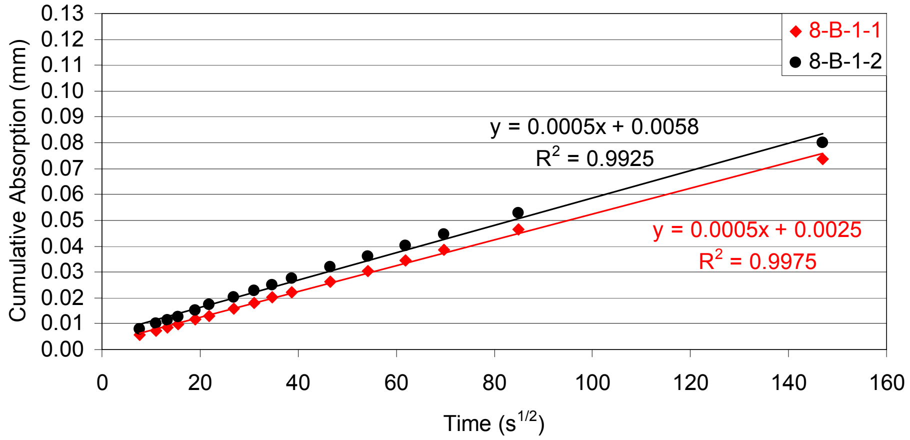


c) Rich bedding mix applied

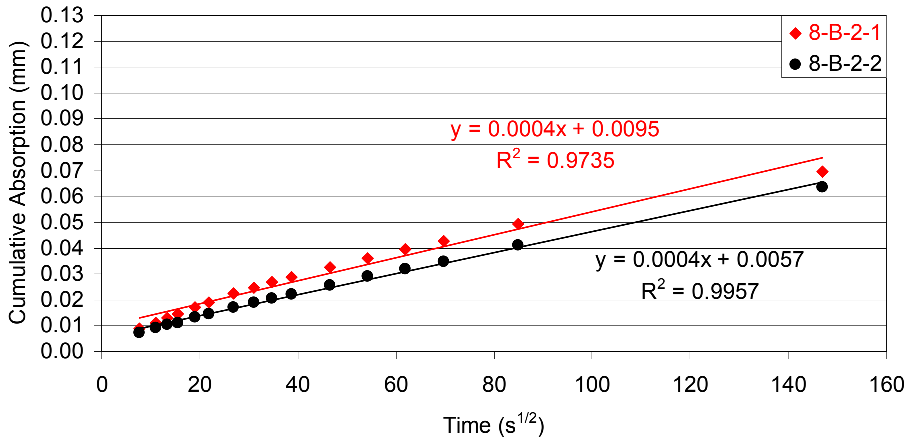
Figure 3.16 Permeability of RCC specimens with 4 hrs time interval between layers



a) No bedding

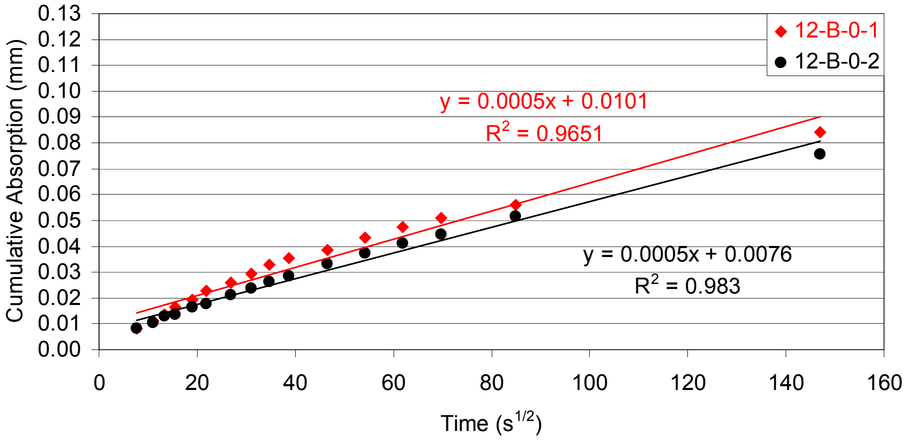


b) Poor bedding mix applied

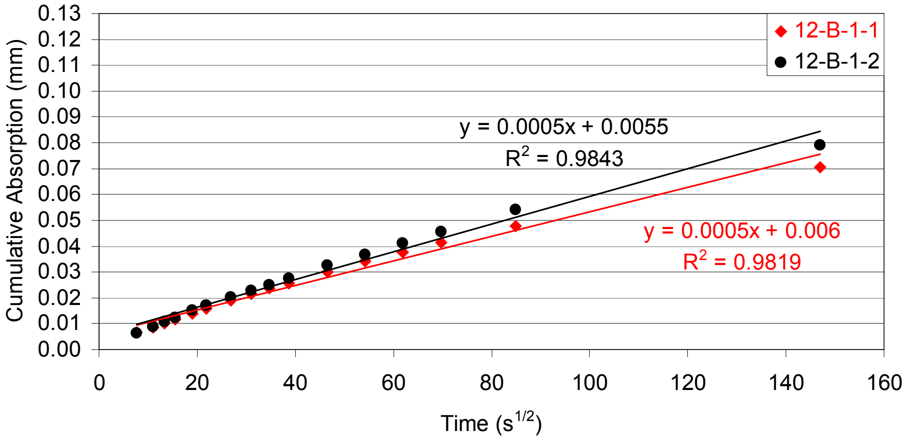


c) Rich bedding mix applied

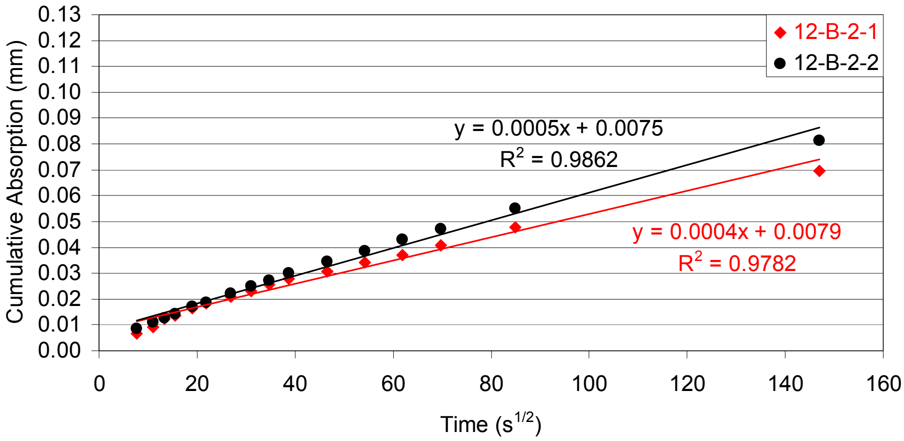
Figure 3.17 Permeability of RCC specimens with 8 hrs time interval between layers



a) No bedding

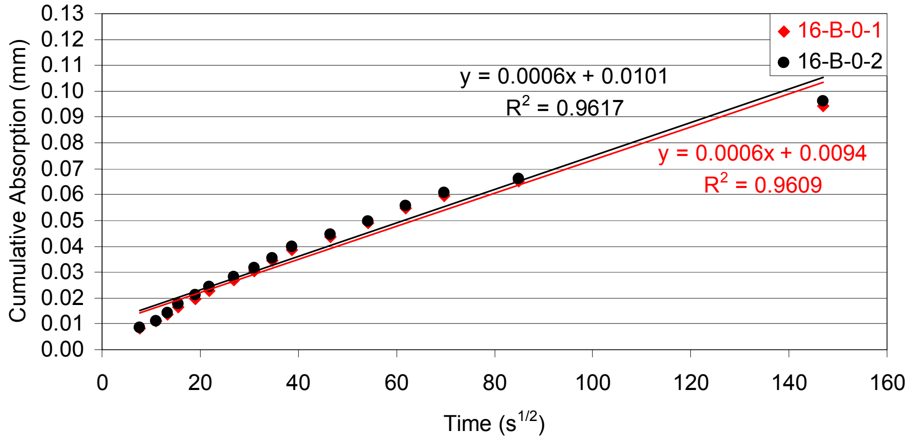


b) Poor bedding mix applied

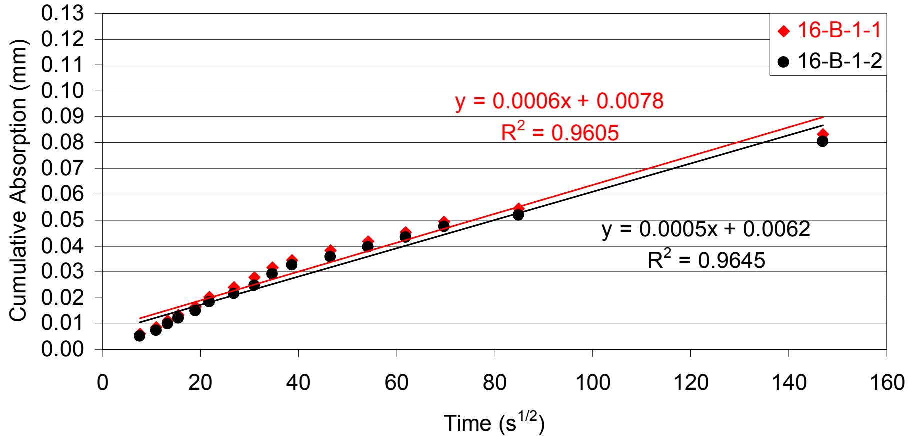


c) Rich bedding mix applied

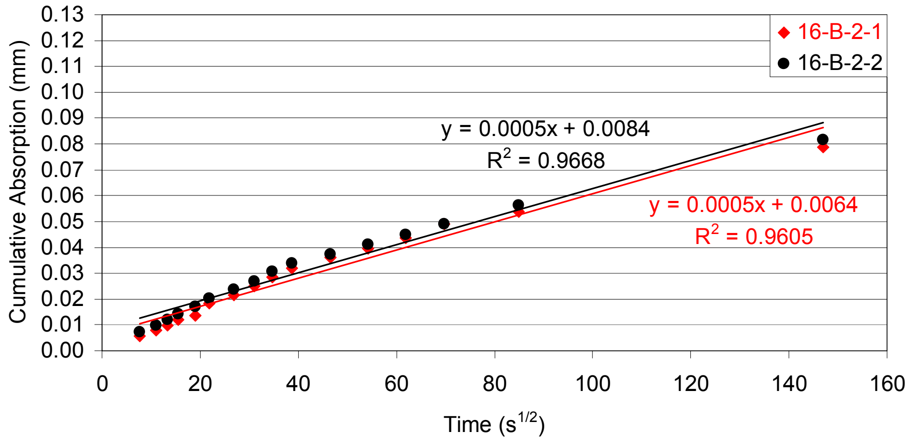
Figure 3.18 Permeability of RCC specimens with 12 hrs time interval between layers



a) No bedding



b) Poor bedding mix applied



c) Rich bedding mix applied

Figure 3.19 Permeability of RCC specimens with 16 hrs time interval between layers

90-day sorptivity index (S_0) and cumulative absorption values for combinations of RCC and bedding mixes are given in Table 3.16. In the table mean and coefficient of variation values of both parameters are also provided.

Table 3.16 90-day sorptivity index (S_0) and cumulative absorption values for combinations of RCC and bedding mixes

Mix ID	**Sorptivity Index, S_0 (mm.s$^{-1/2}$) (10^{-4})**				**Cumulative Absorption at the end of 6 hours (mm)**			
	Specimen No		**Mean**	**COV (%)**	**Specimen No**		**Mean**	**COV (%)**
	#1	**#2**			**#1**	**#2**		
0-B-0	2.02	2.54	***2.28***	***16.0***	0.031	0.038	***0.035***	***14.3***
0-B-1	5.70	5.12	***5.41***	***7.5***	0.085	0.077	***0.081***	***7.0***
0-B-2	5.90	4.87	***5.39***	***13.5***	0.086	0.074	***0.080***	***10.6***
4-B-0	5.32	4.12	***4.72***	***18.0***	0.079	0.062	***0.071***	***17.1***
4-B-1	5.46	5.65	***5.56***	***2.4***	0.085	0.085	***0.085***	***0.0***
4-B-2	5.38	5.80	***5.59***	***5.3***	0.082	0.090	***0.086***	***6.6***
8-B-0	4.63	3.98	***4.30***	***10.6***	0.074	0.063	***0.069***	***11.4***
8-B-1	5.00	5.29	***5.14***	***4.1***	0.074	0.080	***0.077***	***5.5***
8-B-2	4.46	4.07	***4.26***	***6.3***	0.070	0.064	***0.067***	***6.3***
12-B-0	5.46	4.97	***5.21***	***6.6***	0.084	0.076	***0.080***	***7.1***
12-B-1	4.73	5.37	***5.05***	***8.9***	0.071	0.079	***0.075***	***7.5***
12-B-2	4.49	5.36	***4.93***	***12.4***	0.070	0.081	***0.076***	***10.3***
16-B-0	6.41	6.48	***6.45***	***0.8***	0.094	0.096	***0.095***	***1.5***
16-B-1	5.58	5.46	***5.52***	***1.5***	0.083	0.080	***0.082***	***2.6***
16-B-2	5.44	5.44	***5.44***	***0.0***	0.079	0.081	***0.080***	***1.8***

The results of the 90-day specimens for only bedding mix specimens B-1 (poor) and B-2 (rich) are given in Figure 3.20 and 3.21, respectively.

90-day sorptivity index (S_0) and cumulative absorption values for specimens made of bedding mixes are given in Table 3.17 with mean and coefficient of variations.

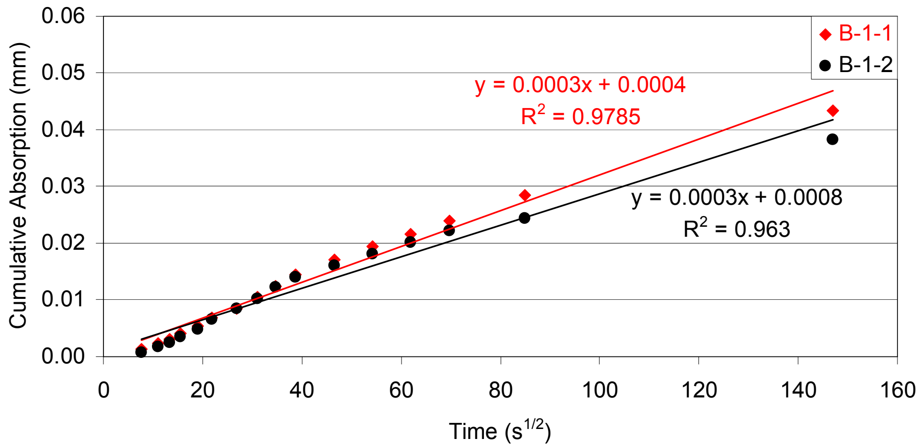


Figure 3.20 Permeability results of poor bedding mix (B-1) specimens

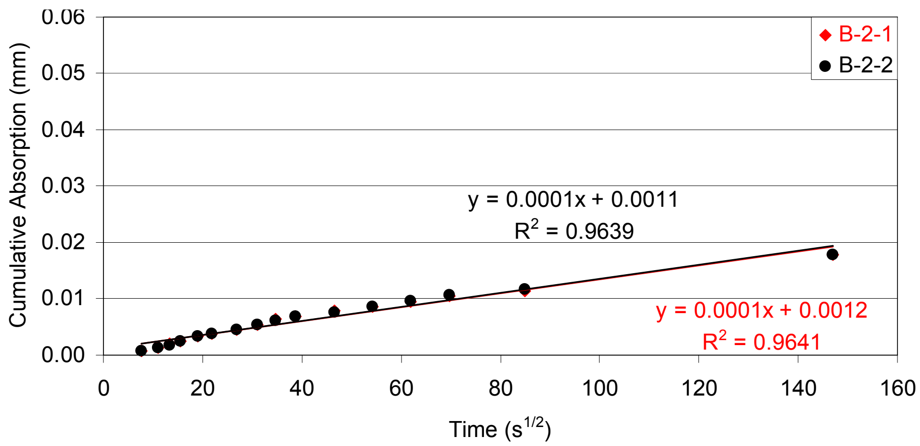


Figure 3.21 Permeability results of rich bedding mix (B-2) specimens

Table 3.17 90-day sorptivity index (S_0) and cumulative absorption values for bedding mixes

Mix ID	Sorptivity Index, S_0 (mm.s$^{-1/2}$) (10^{-4})				Cumulative Absorption at the end of 6 hours (mm)			
	Specimen No		Mean	COV (%)	Specimen No		Mean	COV (%)
	#1	#2			#1	#2		
B-1	3.16	2.79	***2.97***	***8.8***	0.043	0.038	***0.041***	***8.7***
B-2	1.23	1.25	***1.24***	***0.9***	0.018	0.018	***0.018***	***0.0***

CHAPTER 4

DISCUSSION OF RESULTS

The RCC mix utilized in this study was obtained from Beydağ Project RCC studies. Therefore, only hardened properties (compressive strength, splitting tensile strength and permeability) were determined in the laboratory which is in line with the objectives of the study.

4.1 Compressive Strength

In Figure 4.1, 28-day and 90-day compressive strength test results vs. time intervals between compaction of successive layers of RCC are given schematically for different bedding mortar applications and unbedded specimens. As seen from the figure, there are differences between the compressive strength results obtained for bedded and unbedded specimens as well as the time interval the bedding mix was applied. When the 28-day and 90-day compressive strength values are compared, the 90-day compressive strength values are almost two times of 28-day compressive strength values. In addition, when compared to the RCC mix studies performed in the Beydağ Project, at the end of 90 days, all RCC specimens provide the design strength of 6.8 MPa (cylinder specimen) as given in Section 2.7. Therefore, it is concluded that the proper compaction equipment and method has been used in the experimental work.

Moreover, as can be seen in Figure 4.1a, 28-day compressive strength regression lines of poor (B-1) and rich (B-2) bedding mixes applied specimens show a small increasing trend whereas unbedded (B-0) specimens show relatively higher decreasing trend when the time interval between two successive layers increases. For this reason, it is concluded that the 28-day compressive strength of bedding mix applied specimens is not much related to the time interval between compaction of successive layers of RCC.

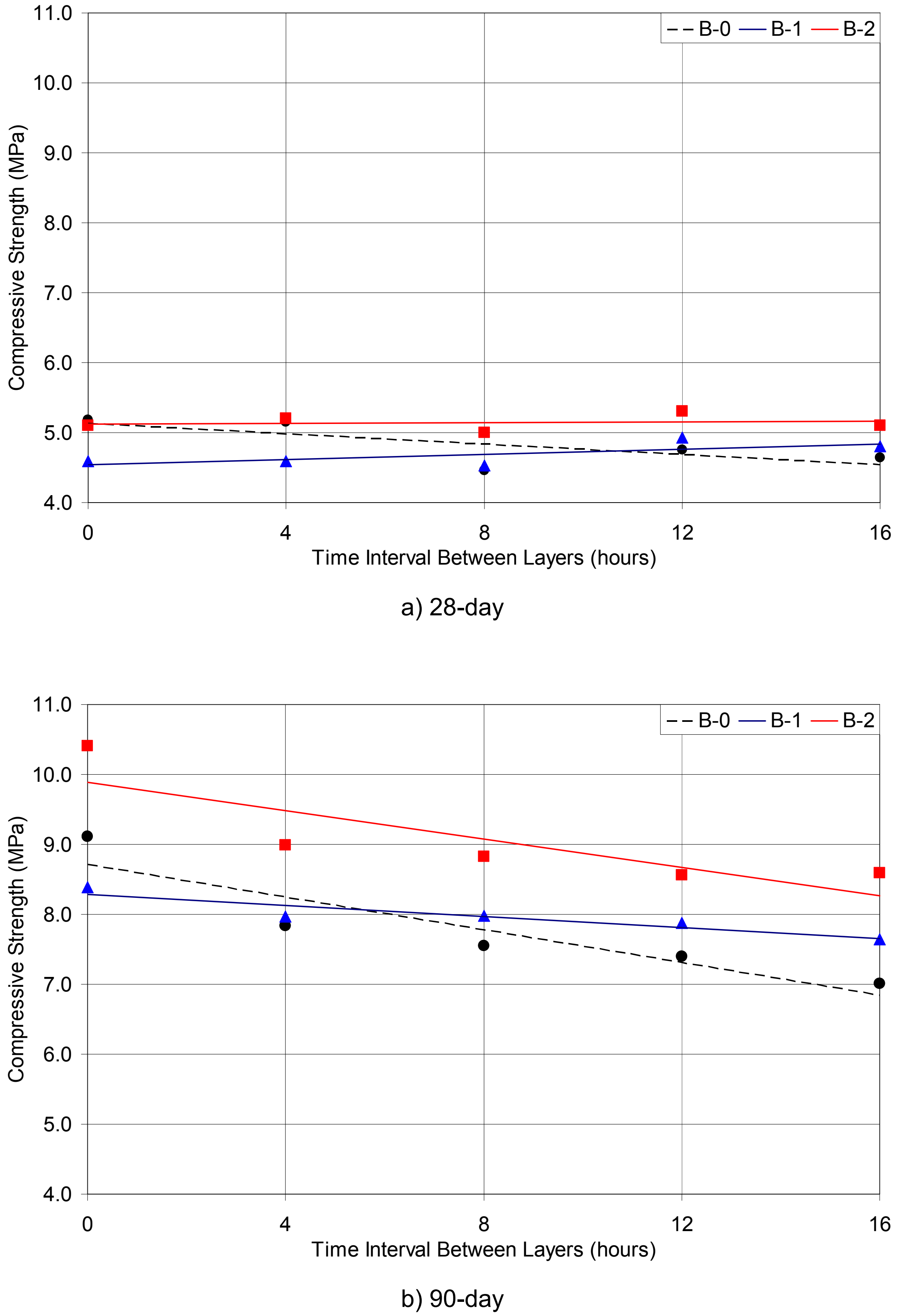


Figure 4.1 Compressive strength vs. time interval between layers

However, 90-day compressive strength regression lines show sharper decreasing trend for both poor and rich bedding mixes applied specimens as compared to 28-day compressive strength results (Figure 4.1b).

Besides this, compressive strength of rich bedding mix (B-2) applied specimens are higher for all time intervals between compaction of successive layers of RCC with respect to poor bedding mix (B-1) applied specimens and unbedded (B-0) specimens.

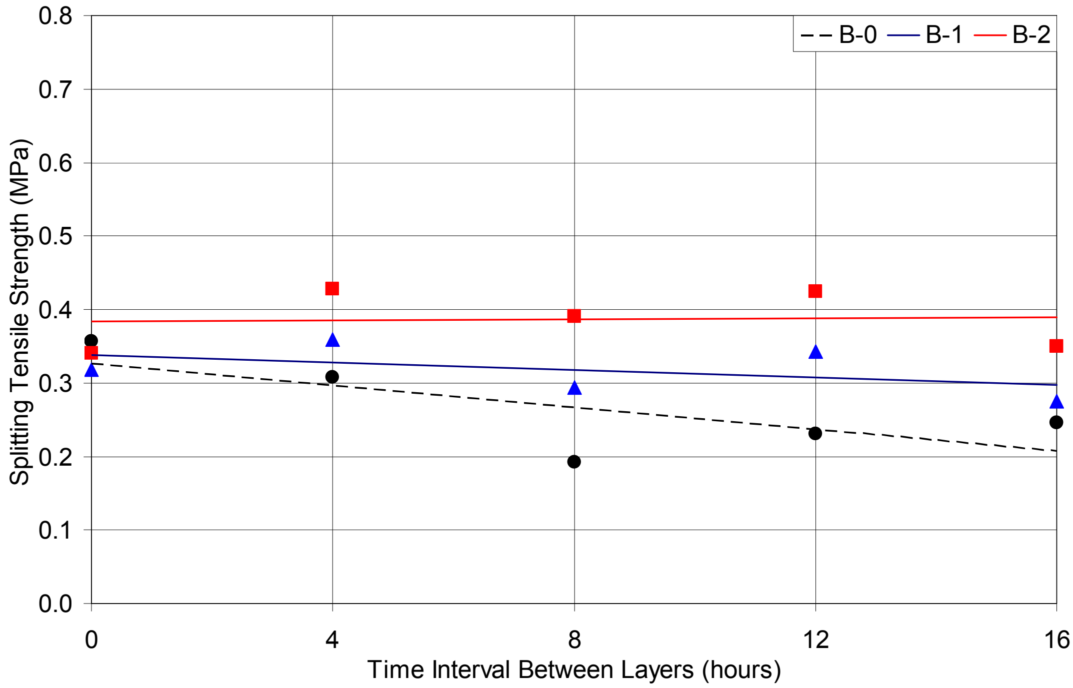
The difference between compressive strengths of unbedded (B-0), poor (B-1) and rich (B-2) bedding mixes applied specimens were more clear at 90-day than 28-day. The highest compressive strength value is obtained for rich bedding mix applied specimens with 0 hour time interval between compaction of successive layers of RCC (0-B-2) as 10.41 MPa for 90-day. Also 90-day compressive strength test gives more accurate results in case the late-age strength development of fly ash is considered.

If 90-day compressive strength regression lines are considered it is clearly seen that, unbedded (B-0), poor (B-1) and rich (B-2) bedding mixes applied specimens all together show decreasing trends as time interval between layers increased, being the highest one unbedded specimens (B-0). In conclusion, at 90 days, when the time interval between compaction of successive layers increases, compressive strength decreases.

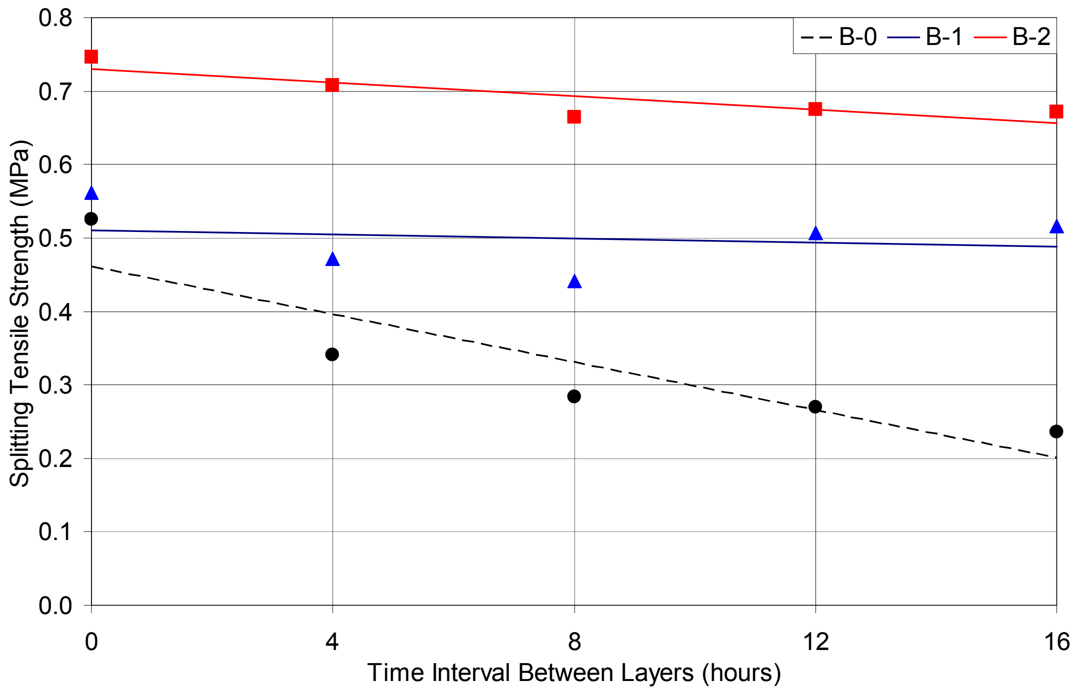
Furthermore, if only bedding mortar specimens were evaluated all together, it is shown that 28-day and 90-day compressive strengths of rich bedding mix (B-2) specimens are almost 4 times as high as that of poor bedding mix (B-1) specimens.

4.2 Splitting Tensile Strength

Figure 4.2 gives 28-day and 90-day splitting tensile strength test results vs. time intervals between compaction of successive layers of RCC specimens for different bedding mortar applications.



a) 28-day



b) 90-day

Figure 4.2 Splitting tensile strength vs. time interval between layers

As seen from the figure, there are differences between the splitting tensile strength results obtained for bedded and unbedded specimens as well as the time interval the bedding mix was applied. Moreover, the 90-day splitting tensile strengths are almost 1.5 times of 28-day splitting tensile strength values.

Moreover, as it is shown in Figure 4.2a, 28-day splitting tensile strength regression lines of rich (B-2) and poor (B-1) bedding mixes applied specimens show small increasing and decreasing trends respectively, whereas unbedded (B-0) specimens show sharper decreasing trend. However, 90-day splitting tensile strength regression lines show small decreasing trend for rich (B-2) and poor (B-1) bedding mixes applied specimens as compared to unbedded (B-0) specimens which show sharp decreasing trend (Figure 4.2b). For this reason, it is concluded that 28-day and 90-day splitting tensile strength of bedding mix applied specimens are not much related to the time interval between compaction of successive layers of RCC.

Furthermore, splitting tensile strength of rich bedding mix (B-2) applied specimens are higher for all time intervals between compaction of successive layers of RCC with respect to poor bedding mix (B-1) applied specimens and unbedded (B-0) specimens.

The difference between splitting tensile strengths of unbedded (B-0), poor (B-1) and rich (B-2) bedding mixes applied specimens were more clear at 90 days than 28 days. The highest splitting tensile strength value is obtained for rich bedding mix applied specimens with 0 hour time interval between compaction of successive layers of RCC (0-B-2) as 0.75 MPa for 90 days.

In addition, if only bedding mortar specimens were evaluated all together, it is shown that 28-day and 90-day splitting tensile strengths of rich (B-2) and poor (B-1) bedding mix specimens are almost same.

4.3 Permeability

90-day cumulative absorption and sorptivity index (S_0) values vs. time interval between compaction of successive layers of RCC are given in Figure 4.3 and Figure 4.4 respectively. As previously explained in Section 3.4.3, the sorptivity test results of 90-day specimens show that the measurement of the absorption up to 6 hours provided acceptable data due to obtained coefficient of correlation, R, values higher than 0.98.

The results of the sorptivity test shows up to 8 to 12 hours time interval between compaction of successive layers, poor (B-1) and rich (B-2) bedding mixes applied specimens are more permeable with respect to unbedded (B-0) specimens (Figure 4.3 and Figure 4.4). In the 0 and 16 hours time interval range the cumulative absorption and sorptivity index regression lines for unbedded (B-0) specimens show sharp increasing trend whereas poor (B-1) and (B-2) rich bedding mixes applied specimens show small decreasing trends. That is, cumulative absorption of unbedded (B-0) specimens increases as time interval between layers increases. At 12 and 16 hours time interval between compaction of successive layers, bedding mortar used RCC specimens show impermeable behaviour with respect to unbedded RCC specimens. For unbedded (B-0) specimens, sharper increasing absorption trend is paralel with the results of compressive strength and splitting tensile strength as time interval between compaction of successive layers is increased.

The permeability test results are parallel with the findings of Xiabin [29] that is bedding the RCC joints with ordinary cement mortar can not improve their impermeability as shown in straight or small decreasing trends of poor (B-1) and rich (B-2) bedding mixes applied specimens.

0-B-0 specimens show smallest cumulative absorption and sorptivity index values as 0.035 mm and 2.28 x 10^{-4} mm.$s^{-1/2}$ respectively, through all RCC specimens. Specimens consist entirely of poor (B-1) and rich (B-2) bedding mixes show 0.041 and 0.018 mm average cumulative absorption values, respectively.

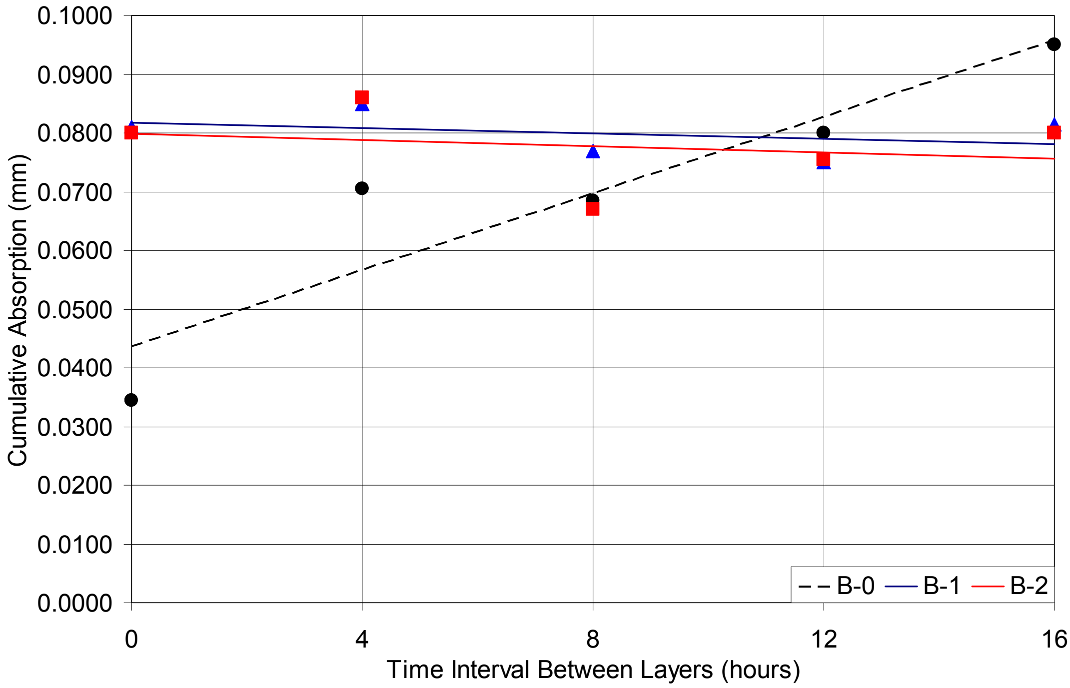


Figure 4.3 90-day cumulative absorption values vs. time interval between layers

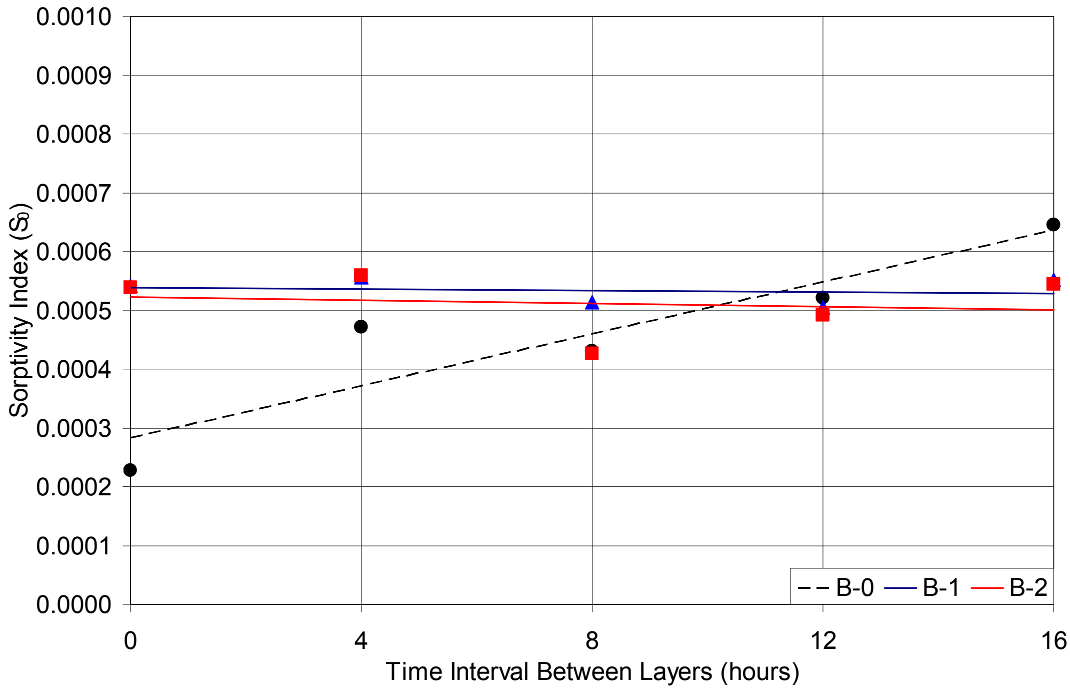


Figure 4.4 90-day sorptivity index (S_0) vs. time interval between layers

CHAPTER 5

SUMMARY AND CONCLUSIONS

This thesis discusses an experimental program carried out at the Materials of Construction Laboratory of M.E.T.U. Civil Engineering Department to investigate the bonding efficiency of roller compacted concrete (RCC) with different bedding mixes. One of the bedding mix is termed a poor mix having 200 kg/m^3 cement content (B-1), while the other one is termed rich having 400 kg/m^3 cement content (B-2). Four different time intervals are used in between compaction of freshly placed RCC layer and formerly compacted RCC layer. As a result of the experimental study, following conclusions could be made:

- Compaction is the most important property of RCC. In the construction site compaction is made with vibrating rollers. However, it is very difficult to realize proper compaction in the laboratory. In the study, it is shown that, an electro pneumatic demolition hammer standardized by ASTM C 1435 can be used for compaction of RCC specimens for laboratory studies.

- Splitting tensile strength and sorptivity tests are shown to be a proper test method for determination of bonding efficiency of RCC specimens if there is a definite bedding layer in between freshly placed and formerly compacted RCC.

- Furthermore, it was also concluded that bonding efficiency of RCC is not too dependent on time interval between compaction of successive layers up to 16 hours.

  For the unbedded specimens the compressive and splitting tensile strengths decrease as the time interval between compaction of successive layers increases. For both of the bedding mixes utilized specimens this reduction in strength is not clearly observed indicating the effectiveness of the bedding mix. Similar results are also obtained on permeability through sorptivity test. Therefore, it can be concluded that the bedding mix when applied properly not only improves the strength but also the permeability properties of RCC up to 16 hours.

Moreover, 90-day compressive strength values are almost two times of 28-day compressive strength values. This result can be explained as contribution of fly ash to the strength development at later ages.

- The rich bedding mix is more effective bonding agent between RCC layers than the poor bedding mix as time interval between layers is increased up to 16 hours and age of specimen is increased.

CHAPTER 6

RECOMMENDATIONS FOR FUTURE STUDIES

As a result of this experimental study, the following recommendations for future studies could be made for other researchers:

- For measurement of splitting tensile strength of RCC specimens there is a definite test method in ASTM C 1245 called the Point Load Test. However, point load test is applicable to cylinder specimens. Therefore, point load test can be applied to cylinder specimens to compare the splitting tensile strength test results of cubic specimens and the results of point load tests.

- More thorough permeability test could be developed and performed in order to determine the hydraulic conductivity of RCC specimens with or without bedding mixes.

- Use of supplementary cementitious materials in the production of bedding mixes could be investigated to reduce the cost of bedding mix.

- Tests can be conducted at later ages than 90 days to make the findings of the experimental study definite.

- Tests can be conducted on larger cylinder and cube specimens for comparison of the findings of the experimental study.

- A comparison between splitting tensile strength test and direct one can be made, if possible.

- A comprehensive study can be made to investigate the effects of surface conditions of RCC layers on the splitting tensile strength and permeability.

For understanding RCC and bedding mix subjects clearly, the problems faced throughout the experimental work are expressed as:

- The fresh properties of RCC mixtures such as workability, setting time and heat generation could be monitored all together to investigate the cold joint formation in between compacted successive RCC layers.

- The same experimental procedures and data could be utilized for more than 16 hours time interval between compaction of successive RCC layers to see the behaviour.

- A test procedure and method could be developed to determine the failure envelope and to understand the shear behaviour of bedded and unbedded RCC specimens under different compressive loads which can be used in RCC structural design.

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