ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

UTILIZATION OF RECYCLED CONCRETE IN STRUCTURAL MEMBERS

M.Sc. THESIS

Sibel İNCE

Department of Civil Engineering

Structure Engineering Programme

JANUARY 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GERİ DÖNÜŞTÜRÜLMÜŞ BETONUN YAPI ELEMANLARINDA KULLANIMI

YÜKSEK LİSANS TEZİ

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Sibel İnce, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** 501111054, successfully defended the **thesis** entitled "**UTILIZATION OF RECYCLED CONCRETE IN STRUCTURAL MEMBERS**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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December 2014 Sibel İNCE
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ABBREVIATIONS

$\boldsymbol{A_c}$: Surface area of the sample
ASR : Alkali silica reaction
Avg : Average
C&D : Construction and Demolition
CEM : Cement type according to DIN EN 197
DAfStb : German Committee for Reinforced Concrete
DIN : German Norm
EN : European Norm
F : Maximum load at failure
FM : Superplasticizer
f : Quantity of microsilica
$\boldsymbol{f_c}$: Compressive strength
g : Quantity of aggregate
k : Fineness modulus
LAGA : Federal Government / Country Working Group on Waste
M : Total weight
NA : Natural Aggregate
p : Volume of air in concrete mixture
pyc : Pycnometer
RAL : German Institute for Quality Assurance and Certification
RC : Recycled Concrete
RCA : Recycled Concrete Aggregate
TS : Turkish Standard
w : Quantity of water
w/z : Water/Cement Ratio
z : Quantity of cement
$\boldsymbol{\rho_f}$: Density of microsilica
$\boldsymbol{\rho_g}$: Density of aggregate
$\boldsymbol{\rho_w}$: Density of water
$\boldsymbol{\rho_z}$: Density of cement

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SUMMARY

This thesis consists of six chapters. In chapter one, the aim of this study is mentioned. In chapter two, literature review about recycled concrete is mentioned. Recycling process and recycling policy in Turkey and Germany is mentioned in chapter three. Concrete mixture proportion and experimental work such as test on aggregate, sieve analysis, pycnometer test, determination of chloride and sulfate content, and test on concrete such as flow table test, compressive strength test, determination of chloride and sulfate content, concrete microstructure and fog chamber test are placed in chapter four. In chapter five sulfate and chloride content of recycled concrete aggregate (RCA) from Istanbul and Berlin, compressive strength test results, flow table test results, sulfate and chloride content of concrete specimens made with RCA from Istanbul and Berlin, fog chamber results and concrete microstructure are mentioned. Concrete mixture proportion is for 50%, 75% and 100% percentage of RCA in concrete mixtures were obtained. The results, analyses, discussion and recommendations are mention in chapter six.

The recycled aggregate were taken from two sources, these were from Istanbul and from Berlin. RCA from Istanbul was consists of recycled demolition waste; whereas, RCA from Berlin was only consists of crushed concrete. RCA from Istanbul was supplied from concrete building which was about 50 years old. Average compressive strength of the core samples was measured 9,3 MPa. Before demolition of the building core samples were taken. Average compressive strength of the core samples was measured 9,3 MPa. RCA from Berlin was supplied from waste water treatment plant which was built on 19th century. Average compressive strength of concrete of this building was about 36 MPa.

Concrete was produced with the different percent of recycled concrete as aggregate in concrete such as 20 %, 50 %, 75 % and 100 % use of recycled concrete. The effects of both fine and coarse RCA on mechanical and physical properties of new structural concrete were investigated. The target of concrete mixtures was obtaining C35 compressive strength class with high content of RCA. For this reason, concrete recipes were found for 50 %, 75 % and 100 % use of RCA. Using different concrete mixture proportions with two different RCA provided the comparison for use of RCA. Cubes with edge length of 15 cm were used to measure compressive strength of concrete. Concrete was poured into the cubes and hardened concrete samples were cured. The development of compressive strength of concrete at the age of 28 days was investigated. Chemical analyses were done for both of RCA and concrete cubes made with RCA. Microstructure of concrete cubes and fog chamber test were implemented to determine weather or not alkali silica reaction occurred.

GERİ DÖNÜŞTÜRÜLMÜŞ BETONUN YAPI ELEMANLARINDA KULLANIMI

ÖZET

Türkiye'de geçmiş depremlerden zarar görmüş çok sayıda bina bulunmaktadır. Yaklaşık olarak depremlerden etkilenen ve düşük beton kaliteli 6,5 milyon betonarme binanın yeni yasaya göre yıkılıp yerine yenilerinin yapılması önümüzdeki 10 yıl için planlanmaktadır. Yıkılması planlanan bu binaların beton kalitesi çok düşük olup, yapım tarihi ise oldukça eskidir. Bu yüzden bu binaların yıkımıyla birçok inşaat yıkıntısı atığı oluşacak. Bu atıkları atık sahasına götürmek çevre kirliliğine, enerji israfına, ekonomik kayıplara ve tarfik sorununa yol açacaktır. Bunun yerine bu inşaat atıkları geri dönüştürülerek betonun içinde agrega olarak kullanılabilir. Geri dönüştürülmüş beton Almanya'da birçok alanda yaklaşık olarak 20 senedir kullanılmaktadir fakat geri dönüştürülmüş betonun Türkiye'de kullanımı ise oldukça sınırlı ve yenidir.

Bu tez altı bölümden oluşmaktadır. Birince bölümde çalışmanın amacından bahsedildi. İkinci bölümde geri dönüştürülmüş betonla ilgili daha önce yapılmış çalışmalardan bahsedildi. Türkiye'deki ve Almanya'daki geri dönüşüm politikaları ve aşamaları üçüncü bölümde anlatıldı. Beton karışım oranları, elek analizi, püknometre deneyleri, geri dönüştürülmüş agregalardaki klorid ve sülfat içeriği deneyleri, beton kıvam tesi, basınç dayanım testi, geri dönüştürülmüş beton kullanılarak yapılan betonlardaki klorid ve sülfat içeriği deneyleri, beton iç yapısı ve sis çemberi testi dördüncü bölümde bahsedilmiştir. Beşinci bölümde Berlin ve İstanbul'dan temin edilen geri dönüştürülmüş agregalardaki klorid ve sülfat içeriği tespitine, basnıç deneylerinin sonuçlarına, beton kıvam tespitine, geri dönüştürülmüş beton kullanılarak yapılan beton numunelerdeki klorid ve sülfat içeriğine, sis çemberi deney sonuçlarına ve beton iç yapısına yer verildi. 50 %,75 % ve 100% oranında geri dönüştürülmüş beton kullanımı için uygun karışım oranları bulundu. Sonuç ve tavsiyelere son bölümde yer verildi.

Bu çalışmanın amacı geri dönüştürülmüş betonun yeni binaların yapımında kullanımını araştırmaktır. İnşaat atıklarının geri dönüştürülerek yeniden kullanımı başta ekonomi ve çevresel açıdan sürdürülebilirlik olmak üzere birçok alanda fayda sağlayacaktır.

Bu çalışma için hem İstanbul'dan hem de Berlin'den geri dönüştürülmüş beton temin edildi. İstanbul'da yıkım prosedürü hakkında bilgi toplamak ve değişik yıkım tekniklerini karşılaştırmak için yıkım aşamasında olan iki bina ziyaret edildi. Bu binalardan ilki Kadıköy de ikincisi ise Zeytinburnu ndadır. İlk bina bitişik nizam olması sebebiyle yıkım işlemi el ile gerçekleşmekteyken ikinci bina ayrık nizam olduğu için yıkım işlemi ekskavatör kullanılarak gerçekleşmekteydi. Bina yıkılmadan önce daha fazla inşaat atığının geri kazanımı ve yeniden kullanılması açısından elle yıkım önemli olsa da zaman açısından oldukça uzun sürmektedir. Bitişik nizam binalarda makine yardımıyla yıkım çevre binalara zarar verme riski

taşıdığı için yıkımın ilk aşamasında elle yıkım tercih edilmektedir. Elle yıkım makina ile yıkıma göre çok uzun sürdüğü için bu çalışma kapsamında ikinci binadan elde edilen inşaat atıkları geri dönüştürülüp kullanıldı. Her iki binadan da karot örnekleri alınmış ve karot raporları tezde sunulmuştur. İlk binanın karot sonuçları oralama olarak 12.22 MPa çıkarken ikinci binanın ortalama karot sonucu 9,3 Mpa çıkmıştır. Berlin'den elde edilen geri dönüştürülmüş beton 19. Yüzyılda yapılan ve su arıtma tesisi olarak kullanılan betonarme bir fabrikanın günümüzde artık kullanılmaması üzerine yıkımı gerçekleştilmiş binadan alındı. Bu binanın oratalama basınç dayanımı 36 Mpa dır.

İstanbul'dan ve Berlin'den alınan geri dönüştürülmüş betona ve doğal agregalara elek analizi yapıldı. İstanbul'dan temin edilen geri dönüştürülmüş beton 0-2 mm, 2-8 mm ve 8-22 mm boyutlarında üç farklı gruba ayrılmaktadır. Berlin'den temin edilen geri dönüştürülmüş beton 0-2 mm, 2-8 mm ve 8-16 mm boyutlarında üç farklı gruba ayrılmaktadır. Bu malzemenin temini Belin'deki beton geri dönüşüm tesisine gidilerek yapıldı. Tesisde bulunan 2-8mm ve 8-16 mm boyutlarındaki malzemeler alındı. 0-2 mm boyundaki malzeme tesiste olmadığı için deneysel çalışmalarda bu boyuttaki doğal agregalar kullanılarak beton üretimi yapıldı. Deneylerde kullanılan doğal agrega ise 0-2, 2-8 ve 8-16 mm boyularında üç farklı gruba ayrılmaktadır. Elek analizi her bir grup için üçer defa yapıldı ve her bir malzemenin farklı boyuttaki her bir grubu için ayrı ayrı agrega granülometri eğrileri çizildi. Her bir grubun incelik modülü hesaplandı.

Berlin'den temin edilen geri dönüştürülmüş beton sadece betondan oluşurken, İstanbul'dan elde edilen geri dönüştürülmüş betonun içinde az miktarda olmakla beraber kiremit, mermer ve tuğla parçaları gibi yabancı maddeler de bulunduğu görüldü ve bu yabancı maddeler mümkün olduğunca ayıklandı.

Geri dönüştürlmüş betonların ve doğal agregaların özgül ağırlıklarının belirlenmesi için püknometre deneyi yapıldı. Deneyden önce malzemeler fırında ısıtılarak bir gün bekletildi. Ertesi gün fırından alınan malzemeler püknometrenin içine konularak kalan hacim suyla doldurulmuş ve 24 saat bekletilmiştir. 24 saat sonra gerekli ölçümler yapılarak özgül ağırlıklar hesaplandı. Geri dönüştürülmüş betonların ve doğal agregaların su emmesi de benzer şekilde tespit edildi.

Deneylerde CEM II/B (S-LL) 42,5 sınıfı çimento, Microsilica Grade 940 U tipi mikrosilika ve ADVA Flow 342 (BV_FM) tipi super plastikleştirici kullanıldı.

Berlin'den ve İstanbul'dan temin edilen geri dönüştürülmüş beton için kimyasal analiz yapıldı. Kimyasal analiz benzer şekilde hazırlanan 20% geri dönüştürülmüş beton kullanılarak üretilen beton ve 50% geri dönüştürülmüş beton kullanılarak beton küpler için de yapıldı. Her iki durum için elde edilen değerlerin çoğu yönetmelike belirlenensınır değerlerin altında olduğu için geri dönüşmüş betonun beton üretiminde agrega olarak kullanılmasında bir sakınca olmadığı tespit edildi.

Bu çalışma kapsamında üretilen betonun basınç dayanımını ölçmek için 15x15x15 cm boyutlarında küp kalıpları kullanılarak beton döküldü. İlk önce 20% oranında geri dönüştürülmüş beton kullanılarak beton döküldü. Daha sonra ise su ve çimento oranı aynı tutularak 50% oranında karışım hazırlandı. 50% oranında karışım hazırlanırken beton daha fazla suya ihtiyaç duydu. Bir sonraki 50% geri dönüştürülmüş beton kullanılarak yapılan karışımda yeni su/çimento oranı dikkate alınarak hazırlandı. Aynı su/ çimento oranı kullanılarak 100% geri dönüşümlü beton kullanılarak yeni bir karışım daha hazırlandı. Bu karışım hazırlanırken de betonun su isteğinde bir artış meydana geldi. 100% geri dönüşümlü beton kullanılarak oluşturulan karışım ve 50% geri dönüşümlü beton kullanılarak oluşturulan karışımınlardaki karışım oranları göz önünde bulundurularak 75% oranında geri dönüştürülmüş beton kullanılarak yeni bir karışım hazırlandı.

Su/çimento oranı aynı tutularak karışımın içindeki geri dönüştürülmüş betonun oranını arttırılarak, geri dönüştürülmüş betonun betonun basınç dayanımına ve özgül ağırlığına olan etkisi ve geri dönüşmüş betonun sebep olduğu su ihtiyacı belirlendi. Bu beton karışımları hem İstanbul'dan temin edilen geri dönüştürülmüş beton kullanılarak yapılmış hem de Berlin'en temin edilen geri dönüştürülmüş beton kullanılarak yapıldı.

Berlin'den temin edilen geri dönüştürülmüş betonda 0-2 mm boyutunda malzeme olmadığı için bu boyuttaki malzeme ihityacı agregadan karşılandı. İstanbul'dan temin edilen geri dönüştürülmüş beton kullanılarak hazırlanan karışımlarda ise geri dönüştürülmüş beton tüm boyutlar da karışıma dahil olmaktadır. Bu durumda yapılan deneylerde ince boyuttaki geri dönüştürülmüş betonun, betonun davranışına olan etkisinin incelemesi sağlamıştır. Çünkü 0-2 mm boyutunda geri dönüştürülmüş beton ile yapılan betonlar 0-2 mm boyutunda agrega kullanılarak hazırlanan karışımlardan daha fazla su ihtiyacına sahip olmaktadır, daha az basınç dayanımına sahiptir ve yoğunlukları daha düşüktür.

Istanbul'dan ve Berlin'den temin edilen geri dönüştürülmüş betondaki sülfat ve klorür içeriği, su emme oranı DIN EN 4226-100 Alman yönetmeliğinde verilen şartları sağlamaktadir. Istanbul'dan ve Berlin'den temin edilen geri dönüştürülmüş beton kullanılarak üretilen betonlardaki sülfat ve klorür içeriği de DIN EN 4226-100 Alman yönetmeliğinde verilen şartları sağlamaktadir. Istanbul'dan ve Berlin'den temin edilen geri dönüştürülmüş beton kullanılarak üretilen betonlara sis çemberi analizi yapılmış ve betonunların iç yapı özellikleri mikroskopla incelenmiştir. Her iki grupta da alkali silika reaksiyonu gözlenmemiştir. Geri dönüştürülmüş beton kullanılarak üretilen betonlara yapılan kıvam testleri de yönetmelik şartlarını sağlamaktadır.

Geri dönüştürülmüş betonun yapı elemanlarında kullanımı yönetmelikte belirtilen kontroller yapıldıktan sonra eğer herhangi bir olumsuz sonuç vermiyorsa kullanılabilir. Yapılan çalışmalarda geri dönüştürülmüş betonun agrega olarak betonda kullanımı, doğal agrega ile yapılan betonlara göre daha fazla su ihtiyacına sebep olmaktadır. Bu ihityacın sebebi ince boyuttaki malzemelerdir. Daha verimli sonuçlar elde etmek için ince boyuttaki malzemeler doğal agregalardan seçilmek kaydıyla karışımlar hazırlanabilir.

1. INTRODUCTION

There are many buildings were damaged in Turkey due to earthquakes occurred in the past. According to Urban Transformation Act in Turkey, estimated 6.5 million concrete frame buildings, which built from poor quality concrete and damaged by the earthquakes will be demolished and reconstructed due to the current building codes in the next 10 years [1]. Therefore, there will be a lot of demolition waste in Turkey. Sending this waste from demolished buildings to storage units cause environmental pollution, energy wastage and traffic problems. Only in Istanbul, in 2008 19 million tons, in 2009 143 million tons, in 2010 121 million tons and in 2011 227 million tons of C&D waste were generated. [2]. To decrease these problems, demolition waste can be used as aggregate in concrete.

Currently, almost all Recycled Concrete (RC) in Germany is used in the construction industry more than twenty years. On the other hand, use of RC as aggregate in new concrete in Turkey is very limited and is not permitted by the Turkish building code at this time.

There is a growing amount of construction and demolition (C&D) waste occurs in the world. About 850 million tons of C&D waste are generated annually in the European Union (EU). This represents 31% of the total waste generation in the EU [3]. In Germany, about 240 million tons of C&D waste were generated in 2002 that represents 63% of the total waste generation [4].

Using RC in new concrete construction can give many benefits to environment, economy and energy such as providing less consumption of natural resources, preventing environmental pollution due to debris accumulation, leading to less energy use and avoiding traffic because of transferring of debris and natural resources. After demolition of the buildings, demolition waste can be crushed in crusher plants to reuse them in concrete construction. Therefore, these building rubble are converted to valuable resources for concrete production.

1.1 Purpose of Thesis

Concrete recycling is very important in terms of economic and environmental areas. Using of recycled materials provide protection of natural resources, lessen environmental pollution, decrease economic expenses, lower emissions and reduce waste disposal. Recycling can turn the waste concrete into a resource.

The purpose of thesis is utilization of recycled concrete (RC) in structural members and obtaining C35/45 compressive strength class by using a large amount of RCA in concrete. For this reason, concrete recipes were found for 50 %, 75 % and 100 % use of RCA. The effects of recycled concrete aggregate (RCA) on concrete is determined. Fresh and hardened properties of concrete made with RCA were obtained experimentally. The effects of both fine and coarse RCA on mechanical and physical properties of new structural concrete were investigated.

2. LITERATURE SURVEY

Ruehl (1997), compared water absorption capacity of recycled demolition rubbish in different densities. For this study, three density classes were defined which are: $\rho < 2$ kg/dm^3, $2 \leq \rho < 2{,}3$ kg/dm^3 and $\rho \geq 2{,}3$ kg/dm^3. In order to determine the water absorption performance, materials were dried to constant weight and sieved into the grain size ranges 4/8, 8/16 and 16/32 mm. After the dry density determination, the dry weight of the material was measured and it was stored 10 minutes under water. After this 10 minutes the weight was measured again to calculate the value of water absorption after 10 minutes of water immersion. The same procedure was done to get the value for water absorption after 24 hours of water immersion. As a result of the tests it was obtained that, water absorption capacity increases when dry density decreases [5].

Lemmer, Ruehl and Nealen (1998), discussed the influence of the type of cement, fly ash, environmental-temperatures, time of the addition of superplasticizer and kind of superplasticizer to consistency of concrete made with aggregate derived from concrete rubble. For the experiments these materials were used: wet recycled concrete having 2/8, 8/16 and 16/32 mm fractions, Portland cements CEM I 32,5 R and CEM I 42,5 R, superplasticizer FM 26 based on Naphthalinsulfonat and FM 29 based on Melaminharz. After mixing the concretes, samples were exposed three different environment temperatures; 5°C, 20°C and 40°C. As a conclusion, fly-ash-addition, superplasticizer, environmental temperature, cement-type and addition-time have no significant influence on the effectiveness of an addition of superplasticizer. Improvement of consistency depends to addition used superplasticizer [6].

Huang, Lin, Chang and Lin (2002), discussed mechanical sorting process of recycling of C&D waste with technical, institutional, and economic considerations. Mechanical sorting process that was consisting of bar screening, trommel screening, air classifier, disk screening, and final manual sorting were analyzed recycling of C&D waste [7].

Khatib (2005), compared concrete containing crushed concrete and crushed brick. The water/cement ratio was same for all mixes. 0%, 25%, 50% and 100% crushed concrete or crushed brick used as fine aggregate with particles less than 5 mm in diameter in concrete mixtures. Strength reduction of concrete made with crushed concrete was 15–30%; on the other hand, concrete made with up to 50% crushed brick had similar long-term strength to concrete made with NA. When concrete was made with 100% crushed brick, the reduction in strength was only 10% [8].

Xiao, Li and Zhang (2005), fabricated and tested concrete specimens with different recycled concrete aggregate contents, which were 0%, 30%, 50%, 70% and 100% percentages of RCA. Compressive strength and other mechanical properties were determined experimentally. At the end it can be said that, analytical expressions for concrete made from RCA can be directly used in theoretical and numerical analysis as well as design of structures [9].

Falkner, Sun and Xiao (2005), investigated seismic performance of frame structures with RCA. 0%, 30%, 50% and 100% RCA were used in concrete samples. Seismic performance was tested. When the percent of RCA was increased in concrete general seismic behavior was decreasing but test samples made with a high percentage of RCA could resist an earthquake according to Chinese standard GB 50011-2001 [10].

Yonar, Koken and Koroglu (2008), studied with 3 different concrete mixtures to obtain 20 MPa compression strength. The first mixture was made with only recycled aggregates. The second mixture contains recycled and normal aggregates. The third mixture was formed with normal aggregates. All concrete mixtures produced with same dosage and water/cement ratio. According to the test results obtained, it was seen that compression strength of concrete decreased with the increasing amount of recycled aggregates [11].

Tam (2008), made the economic comparison of concrete recycling by examining comparative study on costs and benefits between the current practice and the concrete recycling method. As a result, RCA can provide a cost effective method for the construction industry, saving environment and construction sustainability [12].

Durmus, Can and Simsek (2009), produced concrete according to C20, C25, C30 and C35 concrete strength classes. After the determination of engineering properties of the samples for C20, C25, C30 and C35 concrete classes, recycled aggregates were obtained separately. Samples, which have 10*20 cm dimensions, were produced by using recycled aggregates. 7 and 28 day aged samples were tested for the unit weight, ultra sound and compression tests. In test results, the compression strength of concretes was obtained to approach the strength values belonging to a lower concrete class [13].

Achtemichuk, Hubbard, Sluce and Shehata (2009), studied the utilization of fine and coarse RCA with slag or fly ash to produce controlled low-strength materials without using Portland cement. The pozzolanic reaction of slag and fly ash was activated by the alkalis and calcium hydroxide present in the residual paste of the RCA. Seven day compressive strengths with slag 70% higher than mixtures with fly ash. It was obtained that the developed controlled low-strength materials were suitable for a wide range of applications especially for structural support and fast hardening [14].

Evangelista and Brito (2009), tested concrete mixes where fine NA was replaced by fine RCA, to determine the relation to water permeability, capillary absorption and chloride diffusion. As a conclusion, water absorption and the non-steady-state chloride migration coefficient increases linearly with the replacement ratio because fine RCA have a more porous structure but carbonation resistance is reduced with the addition of fine RCA to the concrete [15].

Yaprak, Aruntas, Demir, Simsek and Durmus (2011), investigated the effects of the fine RCA on the concrete properties. For this reason, 0%, 10%, 20%, 30%, 40%, 50% and 100% percentage of concrete mixtures were produced with using fine RCA instead of river sand. Unit weight and water absorption ratios and 28-day compressive strength were measured. As a result of this study, for C30 concrete fine recycled aggregate could be used up to 10% ratio, for C25 concrete fine recycled aggregate could be used between 20-50% ratios [16].

Lovato, Possan, Molin, Masuero and Ribeiro (2011), evaluated mechanical and durability properties of concrete by using response surface methodology. Concrete was made for different w/z ratios by using recycled C&D waste. The results show that, increasing of the quantity of recycled aggregate in concrete increases the w/z ratio, water absorption and carbonation depth of concrete. Coarse recycled aggregate has a major influence on the mechanical properties and fine recycled aggregate affects the concrete durability properties [17].

Thomas, Setien, Polanco, Alaejos, Juan (2012), investigated physical and mechanical properties, behavior under accelerated carbonation, water and oxygen permeability of concrete made with RCA and natural aggregate. Considering the mechanical properties, the influence of RCA is worse for the high w/z ratios and durability due to the intrinsic porosity [18].

Manzi, Mazzotti and Bignozzi (2013), tested short and long-term behavior of structural concrete with RCA. RCA was used ranging from 27% to 63.5% of total amount of aggregate in conrete mixture. It was found that a proper assortment of fine and coarse RCA can lead to good structural concrete as using only coarse RCA [19].

Demirel and Simsek (2014), produced concrete with RCA as coarse and fine aggregates. Two types of aggregate were used in concrete production as 0-4 and 4-22.4 sizes. These aggregate groups were replaced with normal aggregates as 0, 10, 20, 30, 40 and 50% ratios in concrete. Compressive strength of concrete specimens were determined in 28 and 90 days. In their study it was obtained that, RCA had a high water consumption demand and concrete produced with NA had higher compressive strength than concrete produces with RCA [20].

Koroglu and Koken, examined mechanical and physical properties of RCA produced from waste concrete. Compressive strength of the waste concrete from demolished building was about 10 MPa. Cylindrical concrete specimens made with 0%, 50% and 100% RCA were tested to determine the compressive strength at the age of 28 days. As a result of this study, compressive strength of the specimens made with 0% RCA were 19,8 MPa, compressive strength of the specimens made with 50% RCA were 15,3 MPa, compressive strength of the specimens made with 100% RCA were 11,2 MPa were obtained[21].

Patil, Ingle and Sathe worked with recycled coarse aggregates to evaluate physical properties of concrete using recycled coarse aggregate. Recycled coarse aggregate were used in concrete in different percentage. As a conclusion, it can be said that the recycled coarse aggregates can be used up to 50 % in concrete for obtaining good quality concrete [22].

3. RECYCLING OF CONCRETE

3.1 General

Many countries have legislation regulations for recycling of construction and demolition waste. Reuse of recycled concrete is supported by governments all around the world. Recycling of construction and demolition waste in percentage of generated amount in European countries was shown in Figure 3.1 and percentage composition and development of recycled construction and demolition waste European countries was shown in Figure 3.2 [23].

European Parliament and the Council of the European Union determined new targets for recycling of C&D waste by 2020 [24], which are :

-By 2020, the preparing for re-use and the recycling of waste materials such as at least paper, metal, plastic and glass from households and possibly from other origins as far as these waste streams are similar to waste from households, shall be increased to a minimum of overall 50% by weight.

-By 2020 the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 170504 in the European Waste Catalogue [25] shall be increased to a minimum of 70% by weight.

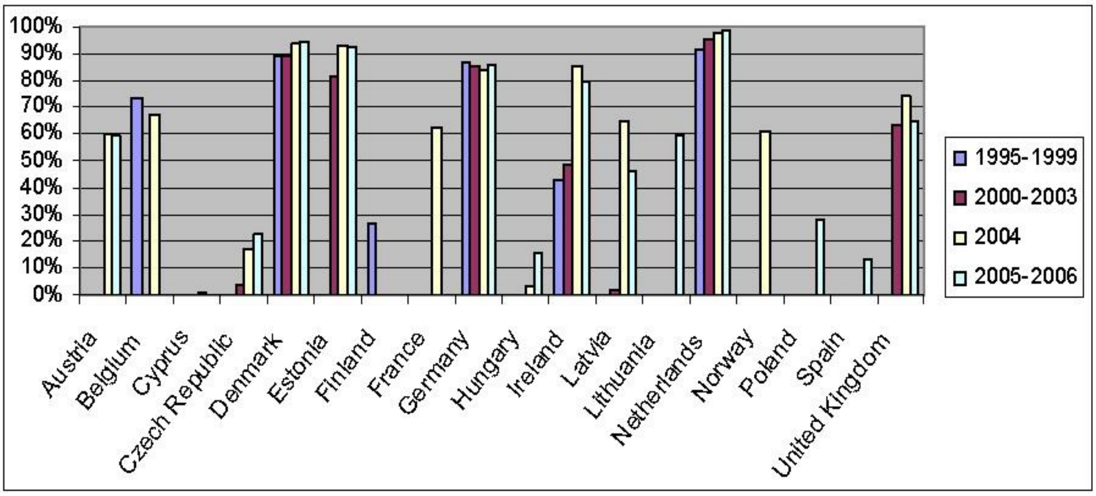


Figure 3.1 : Recycling of C&D waste in percentage of generated amount.

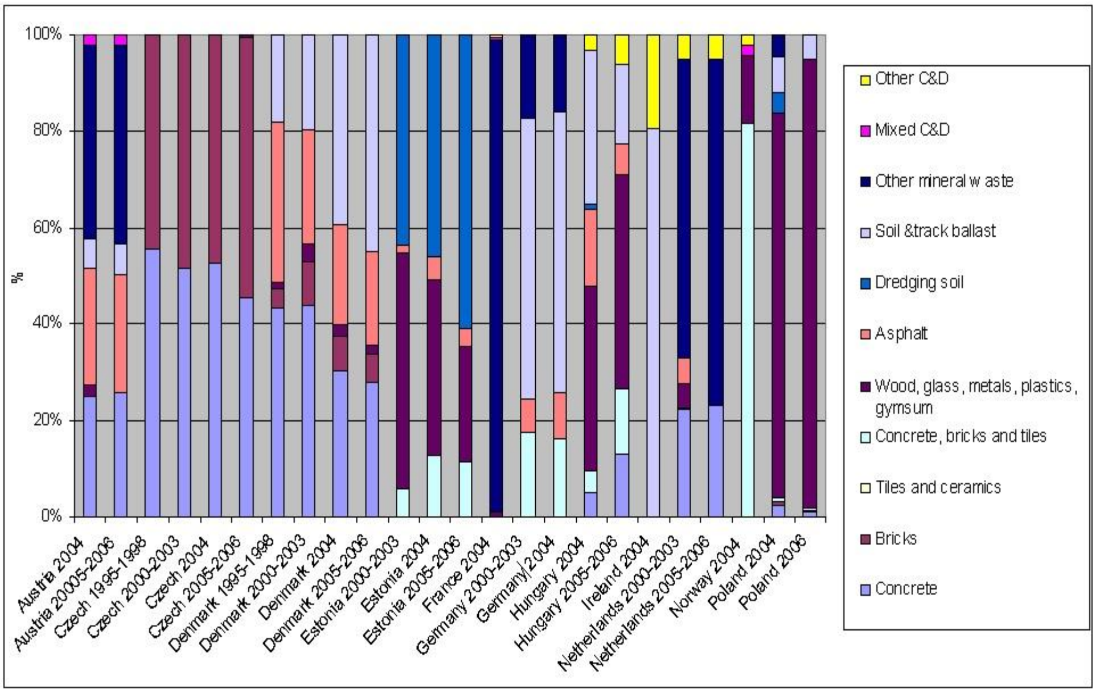


Figure 3.2 : Percentage composition recycled C&D waste.

Recycled C&D consists of concrete, bricks, tiles, asphalt, wood, glass, metals, plastics, gypsum, dredging soil, soil, track ballast, C&D waste and other minerals. Composition of recycled C&D waste in European countries was shown in Figure 3.3 [25].

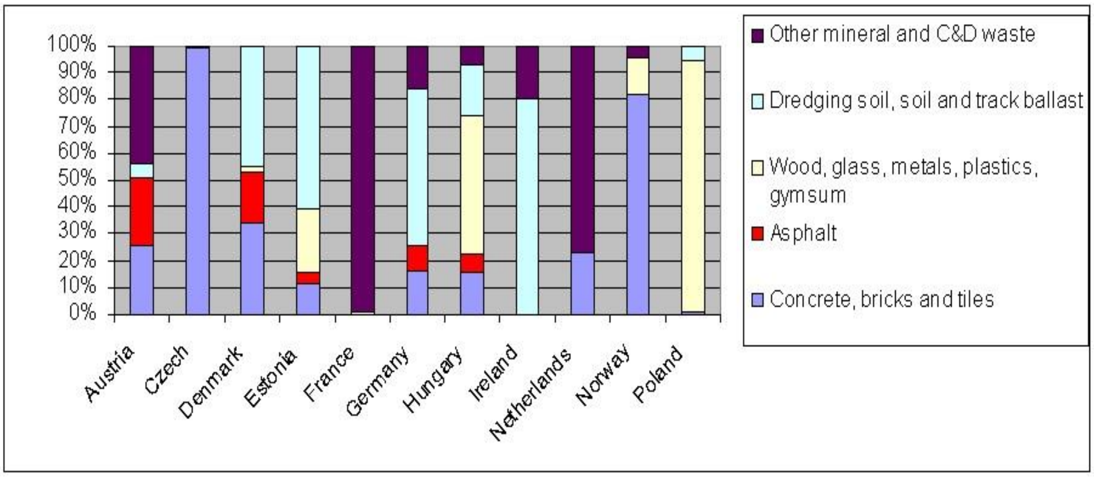


Figure 3.3 : Composition of recycled C&D waste.

3.3 Concrete Recycling in Turkey

3.3.1 Recycling policy

There are many buildings were affected by earthquakes in towns located on fault lines in Turkey. Besides this, there are also many buildings have poor concrete quality. According to the annual report of Ministry of Environmental and Urbanism, areas had disaster risk in Istanbul is 1104.82 hectare and in Turkey is 6,717.30 hectare. For this reason, 161.886 buildings in Turkey and 25.364 buildings in Istanbul were demolished in 2013 [26].

In order to control and monitor C&D waste, Excavation, Construction and Demolition Waste Control Regulation was published in 2004 [27], Construction and Demolition Waste Management was published by Ministry of Environmental and Forestry in 2005 [28] and The National Strategy and Action Plan for Recycling (2014-2017) was published by Ministry of Science, Industry and Technology in 2014 [29].

Recycled plant was built NA at Tuzla in Istanbul in 2008 for reducing C&D waste and saving. In this plant, 66% of C&D waste were recycled in 2008, 54% of C&D waste were recycled in 2009, 60% of C&D waste were recycled in 2010, 51% of C&D waste were recycled in 2011 and 83 % of C&D waste were recycled in 2012. From 2008 to 2012 2.964.9377 tons of C&D waste were recycled and average percentage of recycling is 6%. Amount of recycled materials and their classification according to their sizes from 2008 to 2012 was shown in Figure 3.4 [2].

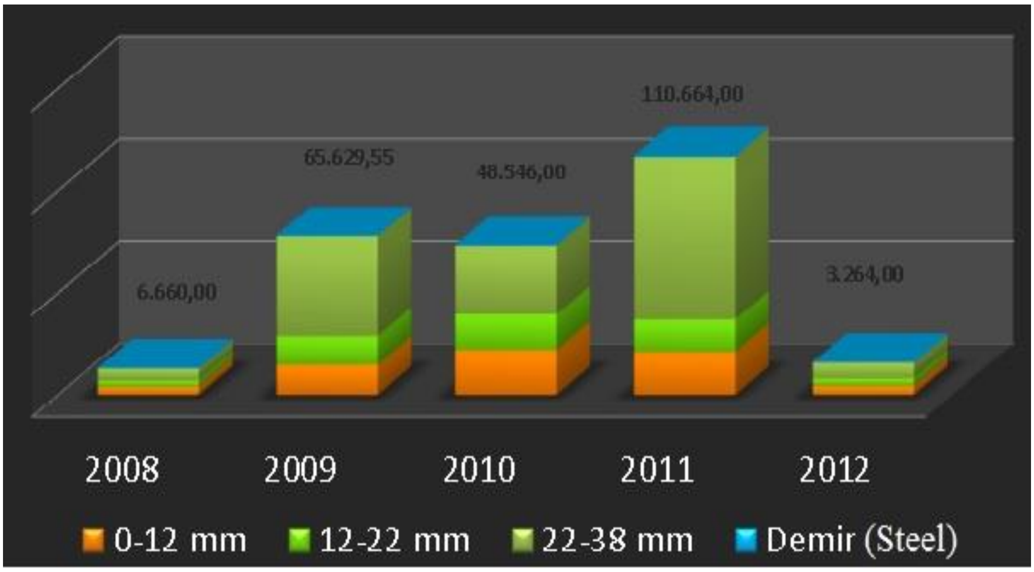


Figure 3.4 : Recycled materials.

RCA are generally used in road construction. Application areas and production of RCA was shown in Figure 3.5 [27].

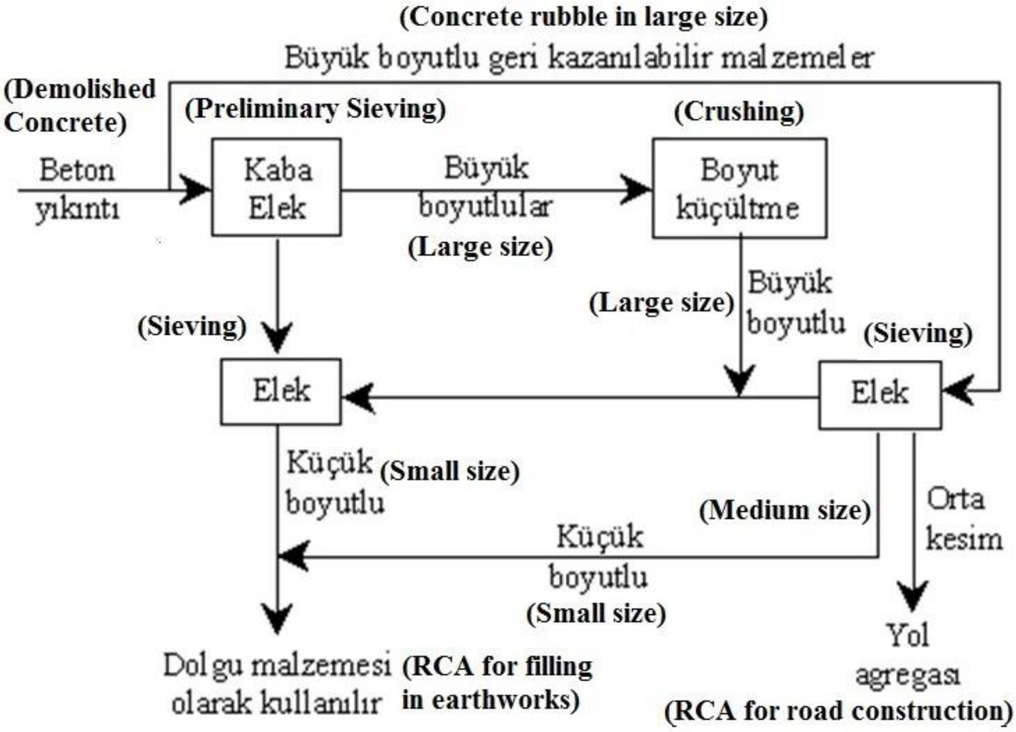


Figure 3.5 : Application areas and production of RCA in Turkey.

3.2.2 Recycling process

3.2.2.1 Demolition of buildings

There are many old buildings are adjacent in Istanbul. If the building will be demonstrated is adjacent to other buildings the demolition process can not be operated by using excavators and other mechanical crushers. In adjacent building demolition by hand is chosen because other methods can damage the other buildings, which are located next to it. During the demolition process of adjacent buildings sledgehammer and other hand tools are used. It is not a quick method, because only hand tools are used and it takes too much time to demolish the building.

Demolition by hand provides to select the materials like wood, brick, tile and steel from interior and exterior demolition for salvaging. Although it is a labor intensive process and very difficult to achieve in timely, it gives opportunity to recover of the maximum amount of primarily reusable and secondary recyclable material in a safe and cost-effective procedure.

For this study, two different buildings under demolition progress were visited in Istanbul. The first building was at Kadikoy and the second building was at Zeytinburnu. The RC was obtained from the second building, which was demolished by mechanical demolition method.

The first building was an adjacent apartment to the other apartments on both sides. The building was surrendered by special sackcloth to prevent dust spread and protect the perimeter from falling rubble. Street view of the first building was shown in Figure 3.6.

Figure 3.6 : Street view of the first building at Kadikoy in Istanbul.

First, doors, windows, kitchen cabinets and other parts of the building, which could be removed easily, were dismantled. Then, slabs were broken with hammer and reinforcing steel bar was cut to provide the openings from one floor to other. Therefore, any sudden collapses because of the unbalanced loads were prevented. Crushed parts of concrete were easily falling down from the openings. Beams and columns were remained in the concrete frame during interior demolition. This procedure was shown in Figure 3.7 and Figure 3.8.

Figure 3.7 : Openings in slabs.

Figure 3.8 : Hand demolition on every floor of the apartment.

Figure 3.9 : Accumulation of debris at the basement.

After that, interior masonry walls were dismantled and therefore crushed wall parts could fall down from the hole of the slabs. This process was repeated from fifth floor to first floor. Debris were accumulated at the basement of the building was shown in Figure 3.9. Dismantlement of interior walls was shown in Figure 3.10 and dismantlement of balconies was shown in Figure 3.11.

Figure 3.10 : Dismantlement of interior walls.

Figure 3.11 : Dismantlement of balconies.

Excavator was used for rest of the demonstration as a final step. Water was used to avoid dust coming from the debris. Demolition by excavator is shown in Figure 3.12. Debris was loaded onto truck and taken to landfilling area in Istanbul.

Figure 3.12 : Demolition by excavator.

Mechanical demolition is an effective method for multi-story structures that have structural damage and much more faster than hand demolition. This method can be applied when the other buildings are away from the building will be demolished. Demolition with ball, deliberate collapse demolition, demolition by using grapples and shears, demolition by explosion, demolition with pusher arm and high-reach demolition excavators are methods of demolition have been using in Istanbul.

The second building was demolished with mechanical demolition. In order to prevent flying dust, water was used during demolition. Demolition procedure was shown in Figure 3.13 and Figure 3.14.

Figure 3.13 : Mechanical demolition.

Figure 3.14 : Last step of mechanical demolition.

Before demolition of building was started, windows and doors were removed and inner walls were crushed. Walls are accepted as a non-structural members in structural design of buildings. Crushing of inner walls of the building was shown in Figure 3.15.

Figure 3.15 : Crushing of inner walls of the building.

3.2.2.2 Preparation of recycling concrete in crusher plant

Reuse and recycling of C&D waste decreases amount of landfilling. Aggregate crushing costs approximately 6,5-7 TL per tonne and sell price is approximately 8-8,5 TL per tonne in aggregate crushing plant. On the other hand, recycling of C&D waste to have RCA costs 3,5-4 TL per tonne and sell price of RCA is approximately 1-1,5 TL per tonne in recycling plant at Tuzla in Istanbul. Therefore it can be said that, RCA is more economical than NA.

Demolition waste from second building was loaded onto truck and taken to aggregate plant for recycling at Kemerburgaz in Istanbul. 1.500.000 tons of aggregate are produced annually in this aggregate plant. In order to have RC, demolition waste was crushed in different sizes. There are jaw crusher, impact crusher and cone crusher at the crusher plant. The aggregate plant was shown in Figure 3.16. Demolition waste at the aggregate plant was shown in Figure 3.17.

Figure 3.16 : The aggregate plant at Kemerburgaz in Istanbul.

Figure 3.17 : Demolition waste at the aggregate plant at Kemerburgaz in Istanbul.

For primary crushing, the jaw crusher was used. It crushed demolition waste under compression. Jaw crusher consists of two parts these are fixed and moving jaws. The moving jaw forced the demolition waste against the fixed jaw. Demolition waste were crushed between fixed and moving jaws. When the demolition waste got small enough to pass through the opening at the bottom of jaw crusher, the primary crushing was completed. The hopper of the jaw crusher was shown in Figure 3.18 and inside of the jaw crusher was shown in Figure 3.19. The demolition waste was transferred to the hopper of the jaw crusher by excavator was shown in Figure 3.20.

Figure 3.18 : The hopper of the jaw crusher at Kemerburgaz in Istanbul.

Figure 3.19 : Inside of the jaw crusher at Kemerburgaz in Istanbul.

Figure 3.20 : Transportation of demolition waste to the hopper of the jaw crusher.

For secondary crushing, the impact crusher was used. The materials were sent to the cage; this cage had openings at the bottom, the openings had proper size so it was allowed the pulverized material to exit the crusher once it had reached the size requirement. The impact crusher was shown in Figure 3.21.

Figure 3.21 : The impact crusher at Kemerburgaz in Istanbul.

As a final process of crushing, a cone crusher was used. Material that had crushed before entered into the top of the cone crusher; then squeezed and crushed again between the mantle and concave. The cone crusher was shown in Figure 3.22.

Figure 3.22 : The cone crusher at Kemerburgaz in Istanbul.

After the crushed concrete came out from the cone crusher, sieve analysis was done and RCA was classified into three categories: RCA in size of 0-2 mm, 2-8 mm and 8-22 mm. RCA was shown in Figure 3.23.

Figure 3.23 : RCA at aggregate plant at Kemerburgaz in Istanbul.

3.3 Concrete Recycling in Germany

3.3.1 Recycling policy

The first waste disposal act (Abfallbeseitigungsgesetz-AbfG), was published in 1972 [30]. Then, the Law for the Prevention and Disposal of Waste (Abfallgesetz-AbfG) was enacted in 1986 [31].

Act for Promoting Closed Substance Cycle Waste Management and Ensuing Environmentally Compatible Waste Disposal (Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umnweltverträglichen Beseitigung von Abfällen) was published in 1994 and updated in 2000 [32]. Landfilling of C&D concrete is illegal in Germany [7].

LAGA (Bund/Laender Arbeitsgemeinschaft Abfall) Federal Government / Country Working Group on Waste published information and regulations about C&D waste for each federal state of Germany. Certification of recycled C&D is conducted by RAL German Institute for Quality Assurance and Certification (Deutsches Institut fuer Guetesicherung und Kennzeichnung) or DIN standarts [7].

DIN 4226-100:2002-02 is about RCA [33]. Some German norms related to this topic are: DIN 1045-2 [34], DIN EN 206-1[35], DIN EN 206-1/A1 [36] and DIN EN 206-

1/A2 [37] and DIN EN 12620 [38]. The German Ministry of Research promoted a research program called Recycling of Mineral Building Materials to regulate the use of RCA. In addition to DIN EN norms, German Committee for Reinforced Concrete

(DAfStb) published regulations called Concrete with Recycled Aggregates Code in 1998 [39].

RCA is generally used in granular base and sub-base applications, for embankment construction and earth construction works like pavements and road construction. Use of RCA in structural members is not as common as granular base and sub-base applications.

C&D waste mainly consists of construction site waste, excavation waste, demolition waste, gypsum-based construction material and road demolition waste. Most of the demolition waste and road demolition waste is recycled while majority of excavation waste is used for mining installations and majority of construction site waste is used for landfilling shown in Figure 3.24 [7].

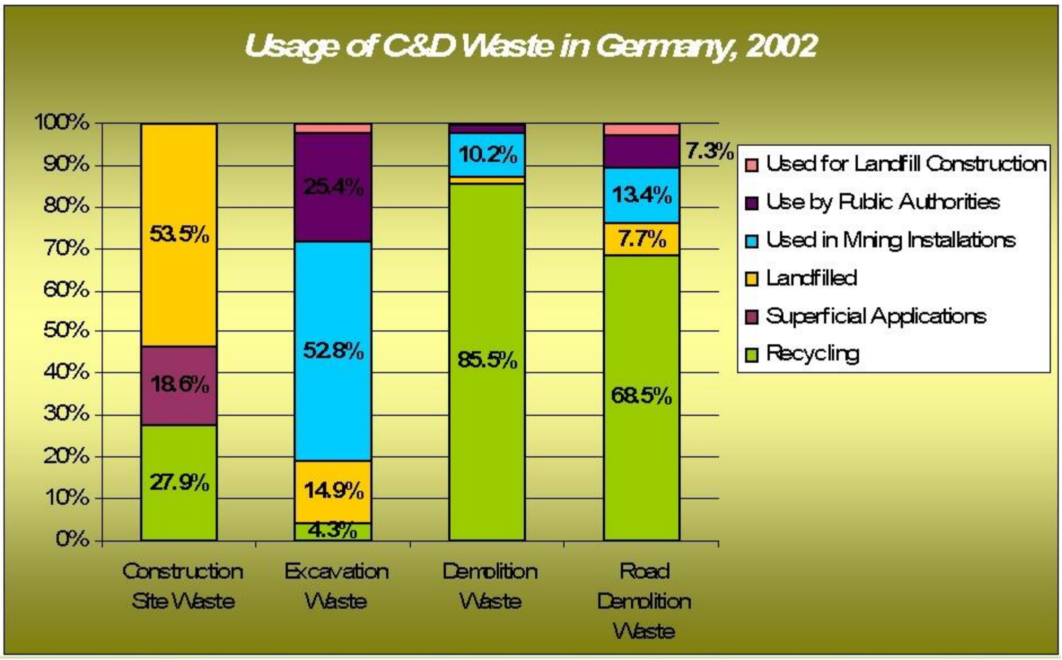


Figure 3.24 : Usage of C&D waste in Germany.

3.3.2 Recycling process

3.3.2.1 Demolition of buildings

Before the demolition, contaminants like windows, doors, glasses etc. and pollutant sources like fireplace, asbestos paneling etc. are removed. Removing of the quantity of nonstructural parts of buildings depends on the demolition type. From conventional demolition to selective demolition, more pieces are dismantled from the building for reusing or recycling separately. Selective demolition is more popular than conventional demolition. Location of the building, cost of demolition, waste disposal costs, internal operating conditions, demolition time are important factors to decide to choose conventional demolition or partial selective demolition or selective demolition will be used. After that, appropriate demolition equipment is chosen according to fallowing factors: demolition costs, occupational safety and health, demolition time, location of the building and type of the building. Demolition with hydraulic excavators is 80%, blasting is 5%, demolition with dragline excavator is 4%, demolition with other mechanical equipment is 3%, demolition with saw and milling is 3%, manual dismantling and small devices are 3%, remote control demolition and demolition robots are 0.3% and other methods are 1,7% in demolition marketing [40].

According to DIN 4226-100, cinder concrete, lightweight concrete, porous brick, plaster, mortar, porous slag and pumice stone are the less convenient materials and glass, ceramic, gypsum, screed and Insulating plasters are the inconvenient materials. It is avoided to have inconvenient materials in recycled concrete. For this reason, Germany Act for Promoting Closed Substance Cycle Waste Management and Ensuing Environmentally Compatible Waste Disposal recommends to separate C&D waste before recycling.

3.3.2.2 Preparation of recycled concrete in crusher plants

In recycling plants, crushing of demolition waste has two stages, which are screening and removing the contaminants. Reinforcing steel, paper, wood, plastics, gypsum are separated from rest of the demolishes by magnetic separation, water cleaning or air sifting. Overlooking of recycled plant where RCA was supplied for this study was shown in Figure 3.25.

Figure 3.25 : Overlooking of the recycling plant at Arkenberge in Berlin.

Jaw crusher and impact crusher were used to prepare RCA. RCA used only consists of concrete because other materials in demolition waste was removed before. The hopper of the crusher was shown in Figure 3.26.

Figure 3.26 : The hopper of the crusher at Arkenberge in Berlin.

The recycled plant at Arkenberge has also mobile crushers. If the demolition waste is homogenous mobile crushers can be used. Mobile crushers give an advantage when demolition waste is reused on site. Mobile crusher at recycled plant was shown in Figure 3.27.

Figure 3.27 : The mobile crusher at Arkenberge in Berlin.

Mobile crushers have separator to collect the inconvenient materials from RC. Before crushing of concrete rubble, materials were sieved and small ones could directly join the band of crushed concrete. Working order of mobile crusher was shown in Figure 3.28 [41].

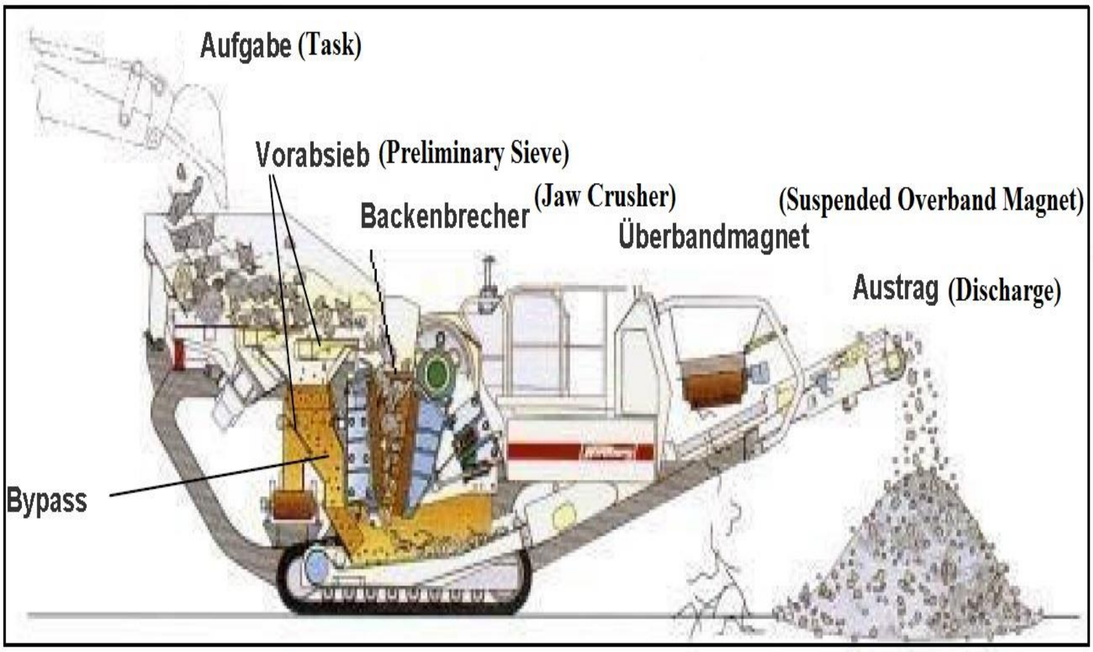


Figure 3.28 : Mobile crusher working principal.

Figure 3.29 : C&D waste and RCA at the recycling plant at Arkenberge in Berlin.

RCA were sieved and sorted into three groups according to their sizes: 0-2 mm, 2-8 mm and 8-16 mm. C&D waste before recycling and RCA at recycling plant were shown in Figure 3.29. RCA size between 8-16 mm was shown in Figure 3.30 and RCA size between 2-8 mm was shown in Figure 3.31.

Figure 3.30 : RCA size between 8-16 mm at Arkenberge in Berlin.

Figure 3.31 : RCA size between 2-8 mm at Arkenberge in Berlin.

4. EXPERIMENTAL WORK

4.1 Materials

4.1.1 Recycled concrete aggregate taken from Istanbul

RCA, which was categorized into three groups according to their sizes which were between 0 and 2 mm, 2 and 8 mm, 8 and 22 mm were shown in Figure 4.1, Figure 4.2 and Figure 4.3.

Figure 4.1 : RCA Istanbul (8-22 mm).

Figure 4.2 : RCA Istanbul (2-8 mm).

Figure 4.3 : RCA Istanbul (0-2 mm).

RCA from Istanbul was supplied from a reinforced concrete frame apartment that had effected by corrosion and previous earthquakes. There were one basement, one ground floor and four normal floors in the apartment. It was about 50 years old. The height of the apartment was 17, 30 m in total.

Before the demolition started, core samples were taken from each floor of the building. In order to avoid the embedded pieces of reinforcing steel bar in core, a metal detector was used to find them. The best place was marked which had no steel reinforcing steel bar for taking out the core. Determination of core location by using metal detector was shown in Figure 4.4. Core samples were taken according to TS EN 12504-1 [42].

Figure 4.4 : Determination of core location.

Cylindrical concrete samples were obtained by rotary core drilling machine, which had long single tube. The single tube was attached to core barrel bit to the drilling machine. The drill was located perpendicular to the concrete surface and ensured the steady still position during drilling until reaching the base. Cores were cut with a rotary cutting tool. Water was used during the drilling operation. Taking core sample from the building was shown in Figure 4.5.

Figure 4.5 : Taking core sample from the building.

After the core removed from the column was shown in Figure 4.6.

Figure 4.6 : Taking out the core from the column.

The cores showed compaction of concrete and distribution of aggregates. 8 cores were taken from the first building which was located in Kadikoy. 18 cores were taken from the second building, which was located in Zeytinburnu. Core samples from the first building were shown in Figure 4.7.

Figure 4.7 : The core samples.

Uneven ends of the core samples were cut by saw at the laboratory. Hence, the ends were made plane and parallel to each other for the compression strength test. After cutting of uneven ends, topping was prepared at the laboratory and applied on both ends of the core samples. This topping provided a plane surface for the compressive strength test. Preparation of cores at the laboratory was shown in Figure 4.8 and Figure 4.9. The topping applied on both sides of core samples was shown in Figure 4.10.

Figure 4.8 : Cutting of uneven ends of the core sample.

Figure 4.9 : Application of topping to the core samples.

Figure 4.10 : The core samples before compressive strength test.

After application of topping, the core samples were taken into compression testing machine as it shown in Figure 4.8. A core sample was aligned centrally on the base plate of the machine and tested under compression by loading on the upper plate of the machine. Compressive strength test was performed for each of core samples one by one according to TS EN 12390-3 standard [43] in Istanbul.

Figure 4.11 : Compressive strength test.

Core samples after the experiment were shown in Figure 4.12 and Figure 4.13.

Figure 4.12 : First group of the core samples after the experiment.

Figure 4.13 : Second group of the core samples after the experiment.

Compressive strength test results of the core samples taken from the first building were shown in Table 4.1. Average compressive strength of the core samples was measured 12,22 Mpa.

Table 4.1 : Compressive strength of the core samples (first building).

Name of the specimen	Maximum Load (kN)	Compressive Strength (MPa)
K1	69,10	9,96
K2	104,10	15,00
K3	74,60	10,74
K4	85,40	12,31
K5	45,00	6,47
K6	111,70	16,09
K7	96,00	13,84
K8	93,00	13,39
Average	84,86	12,22

Compressive strength test results of the core samples taken from the second building were shown in Table 4.2. Average compressive strength of the core samples was measured 9,3 MPa.

Table 4.2 : Compressive strength of the core samples (second building).

Name of the specimen	Maximum Load (kN)	Compressive Strength (MPa)
K1	39	6,1
K2	52	8,1
K3	34	5,3
K4	68	10,6
K5	57	8,9
K6	45	7,0
K7	31	4,9
K8	54	8,4
K9	42	6,6
K10	84	13,1
K11	67	10,4
K12	54	8,5
K13	60	9,4
K14	76	11,9
K15	60	9,5
K16	87	13,6
K17	68	10,6
K18	95	14,9
Average	60	9,3

4.1.1.1 Sieve analysis

RCA was prepared for three different size at crusher plant in Istanbul which were 0-2 mm, 2-8 mm and 8-22 mm. Each group was packaged separately and sent to Berlin Technical University. Determination of particle size distribution with sieve analysis was done for each group of RCA according to DIN EN 933-1 [44]. Set of sieves with given aperture size and sieve shaker were shown in Figure 4.14.

For RCA size between 0-2 mm, 2-8 and 8-22 was sieved three times. 4000 gram material were taken for the sieve analysis each time. According to DIN EN 933-2 [45] the basic series of test sieves are: 0,063 mm; 0,125 mm; 0,250 mm; 0,500 mm; 1 mm; 2 mm; 4 mm; 8 mm; 16 mm; 31,5 mm; 63 mm; 125 mm. RCA taken from Istanbul was sieved from 22,4 mm to 0,063 mm.

Sieve analysis results of RCA size between 0-2 mm were shown in Table 4.3, Table 4.4 and Table 4.5. Sieve analysis results of RCA size between 2-8 mm were shown in Table 4.6, Table 4.7 and Table 4.8. Sieve analysis results of RCA size between 8-22 mm were shown in Table 4.9, Table 4.10 and Table 4.11.

Figure 4.14 : Sieve shaker.

Fineness Modulus, k, was calculated to determine the degree of uniformity of the aggregate gradation according DIN EN 12620. The higher the fineness modulus, the coarser the aggregate. Fineness modulus was calculated with the summarization of cumulative percentages retained on each of the specified sieve divided by 100 is given in Formula **(4.1).**

$$k = \frac{\sum(\mathit{Cumulative\ percentage\ retained\ on\ the\ sieves})}{100} \qquad \textbf{(4.1)}$$

For the first sieve analysis of RCA (0-2 mm): k = 1,56.
For the second sieve analysis of RCA (0-2 mm): k = 1,62.
For the third sieve analysis of RCA (0-2 mm): k = 1,62.
For the first sieve analysis of RCA (2-8): k = 4,58.
For the second sieve analysis of RCA (2-8): k = 4,56.
For the third sieve analysis of RCA (2-8): k = 4,54.
For the first sieve analysis of RCA (8-22): k = 6,10.
For the second sieve analysis of RCA (8-22): k = 6,16.
For the third sieve analysis of RCA (8-22): k = 6,21.

Table 4.3 : First sieve analysis of RCA Istanbul (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
2	100,4	3899,6	2,51	2,51	97,49
1	718	3181,6	17,95	20,46	79,54
0,5	1248,8	1932,8	31,22	51,68	48,32
0,25	1192,4	740,4	29,81	81,49	18,51
0,125	446,4	294	11,16	92,65	7,35
0,063	188,8	105,2	4,72	97,37	2,63
0	105,2	0	2,63	100	0

Table 4.4 : Second sieve analysis of RCA Istanbul (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
2	103,2	3896,8	2,58	2,58	97,42
1	732,8	3164	18,32	20,9	79,1
0,5	1324	1840	33,1	54	46
0,25	1224,8	615,2	30,62	84,62	15,38
0,125	299,6	315,6	7,49	92,11	7,89
0,063	161,6	154	4,04	96,15	3,85
0	154	0	3,85	100	0

Table 4.5 : Third sieve analysis of RCA Istanbul (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Pa ssing (%)
2	101,2	3898,8	2,53	2,53	97,47
1	728,4	3170,4	18,21	20,74	79,26
0,5	1312,8	1857,6	32,82	53,56	46,44
0,25	1268	589,6	31,7	85,26	14,74
0,125	253,2	336,4	6,33	91,59	8,41
0,063	190,4	146	4,76	96,35	3,65
0	146	0	3,65	100	0

Table 4.6 : First sieve analysis of RCA (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	56	3944	1,4	1,40	98,60
4	2416	1528	60,4	61,80	38,20
2	1411,2	116,8	35,28	97,08	2,92
1	45,2	71,6	1,13	98,21	1,79
0,5	53,6	18	1,34	99,55	0,45
0,25	3,6	14,4	0,09	99,64	0,36
0,125	4,4	10	0,11	99,75	0,25
0,063	5,2	4,8	0,13	99,88	0,12
0	4,8	0	0,12	100	0

Table 4.7 : Second sieve analysis of RCA Istanbul (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	56,8	3943,2	1,42	1,42	98,58
4	2339,2	1604	58,48	59,9	40,1
2	1485,2	118,8	37,13	97,03	2,97
1	45,6	73,2	1,14	98,17	1,83
0,5	54,4	18,8	1,36	99,53	0,47
0,25	3,2	15,6	0,08	99,61	0,39
0,125	4,8	10,8	0,12	99,73	0,27
0,063	5,6	5,2	0,14	99,87	0,13
0	5,2	0	0,13	100	0

Table 4.8 : Third sieve analysis of RCA Istanbul (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	54	3946	1,35	1,35	98,65
4	2245,2	1700,8	56,13	57,48	42,52
2	1588,4	112,4	39,71	97,19	2,81
1	43,6	68,8	1,09	98,28	1,72
0,5	52,4	16,4	1,31	99,59	0,41
0,25	3,2	13,2	0,08	99,67	0,33
0,125	4,4	8,8	0,11	99,78	0,22
0,063	4,4	4,4	0,11	99,89	0,11
0	4,4	0	0,11	100	0

Table 4.9 : First sieve analysis of RCA Istanbul (8-22 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
22,4	73,6	3926,4	1,84	1,84	98,16
16	1396,8	2529,6	34,92	36,76	63,24
8	2272	257,6	56,8	93,56	6,44
4	49,6	208	1,24	94,80	5,20
2	20,4	187,6	0,51	95,31	4,69
1	24	163,6	0,6	95,91	4,09
0,5	25,6	138	0,64	96,55	3,45
0,25	24,8	113,2	0,62	97,17	2,83
0,125	24,8	88,4	0,62	97,79	2,21
0,063	50,4	38	1,26	99,05	0,95
0	38	0	0,95	100	0

Table 4.10 : Second sieve analysis of RCA Istanbul (8-22 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
22,4	34,8	3965,2	0,87	0,87	99,13
16	1301,6	2663,6	32,54	33,41	66,59
8	2497	166,8	62,42	95,83	4,17
4	36,4	130,4	0,91	96,74	3,26
2	11,2	119,2	0,28	97,02	2,98
1	12,8	106,4	0,32	97,34	2,66
0,5	14,8	91,6	0,37	97,71	2,29
0,25	14,4	77,2	0,36	98,07	1,93
0,125	15,6	61,6	0,39	98,46	1,54
0,063	44	17,6	1,1	99,56	0,44
0	17,6	0	0,44	100	0

Table 4.11 : Third sieve analysis of RCA Istanbul (8-22 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
22,4	24,8	3975,2	0,62	0,62	99,38
16	1485,2	2490	37,13	37,75	62,25
8	2336	153,6	58,41	96,16	3,84
4	24	129,6	0,6	96,76	3,24
2	8,4	121,2	0,21	96,97	3,03
1	12,8	108,4	0,32	97,29	2,71
0,5	15,6	92,8	0,39	97,68	2,32
0,25	16,8	76	0,42	98,10	1,90
0,125	18	58	0,45	98,55	1,45
0,063	33,6	24,4	0,84	99,39	0,61
0	24,4	0	0,61	100	0

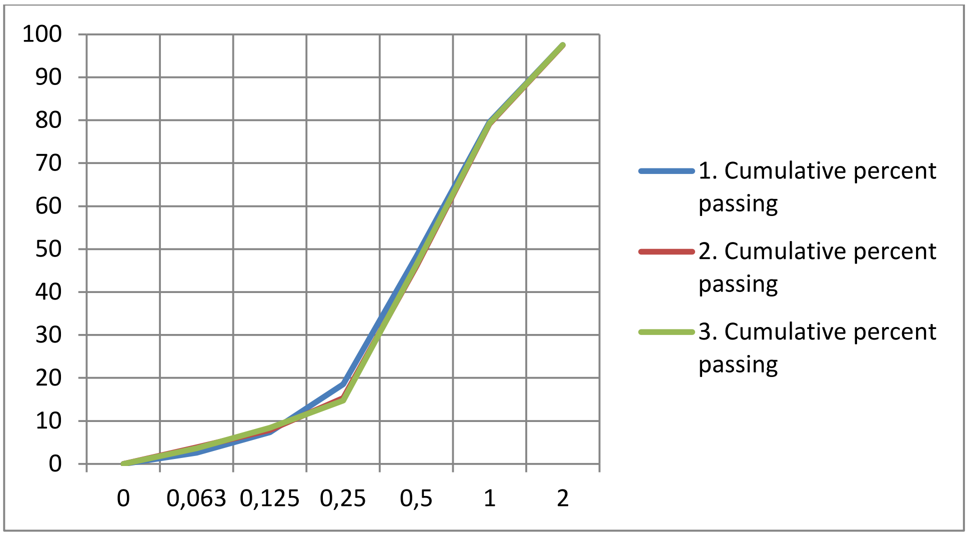


Figure 4.15 : Aggregate grading curves for RCA Istanbul (0-2 mm).

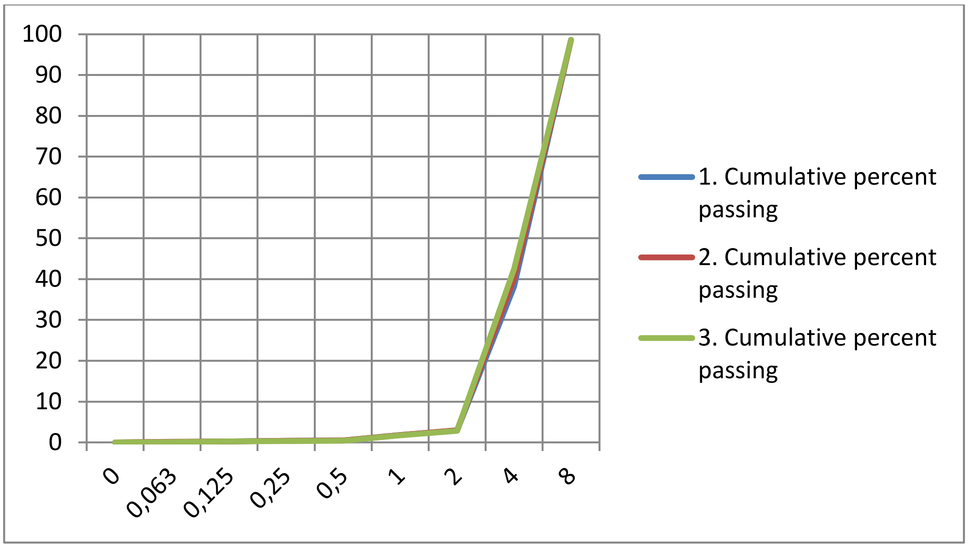


Figure 4.16 : Aggregate grading curves for RCA Istanbul (2-8 mm).

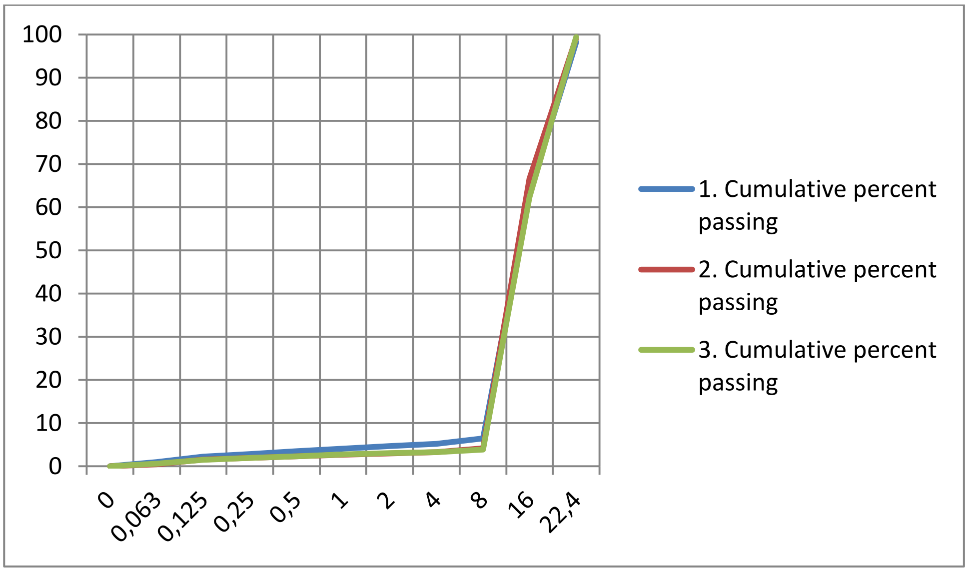


Figure 4.17 : Aggregate grading curves for RCA Istanbul (8-22 mm).

Aggregate grading curves for RCA taken from Istanbul (0-2 mm) were shown in Figure 4.15, 2-8 mm were shown in Figure 4,16 and 8-22 mm were shown in Figure 4,17. k(avg) = 1,60 for RCA (0-2 mm), k(avg) = 4,56 for RCA (2-8 mm), k(avg) = 6,16 for RCA (8-22 mm) were obtained.

4.1.1.2 Pycnometer

In order to determine density of RCA pycnometer analysis was done according to DIN 1097-6 [46]. The pycnometers were shown in Figure 4.18.

Figure 4.18 : The pycnometers.

2000 grams of materials were taken from each group of RCA and put in three pots separately. Then the pots were put in an oven at 110 K and waited 24 hours. All of the materials in the oven were taken out of the oven and 500 grams of materials from each group were taken for the experiment. Pycnometers were filled with water and weighted. After that, 500 grams of materials from each group were put in the pycnometers separately and waited 24 hours. Then each pycnometer was weighted again. Density of materials was calculated according to Formula **(4.2).**

$$\rho = \frac{mg \times 0{,}997}{mg + m(pyc + water) - m(pyc + water + material)} \tag{4.2}$$

In this equation;

ρ : Density of aggregate

mg : Weight of the oven dry materials

m(pyc + water) : Weight of the pycnometer filled with water

m(pyc + water + material) : Weight of the pycnometer filled with water and materials

For RCA (0-2 mm in size):
mg = 500 g
m(pyc + water) = 1955,2 g
m(pyc + water + material) = 2251 g
$\rho = 2,44$ kg / dm^3

For RCA (2-8 in size) mm:
mg = 500 g
m(pyc + water) = 2005,8 g
m(pyc + water + material) = 2313,9 g
$\rho = 2,6$ kg / dm^3

For RCA (8-22 mm in size):
mg = 500,3 g
m(pyc + water) = 2009 g
m(pyc + water + material) = 2316 g
$\rho = 2,58$ kg / dm^3

According to DIN EN 1097-6, aggregate is classified into three groups according to their densities. If $\rho \leq 2$ kg/dm^3, aggregate is defined as light aggregate, if 2 kg/dm^3 $<\rho<3$ kg/dm^3, aggregate is defined as normal aggregate and if $\rho \geq 3$ kg/dm^3, aggregate is defined as heavy aggregate. As mentioned above RCA taken from Istanbul is normal aggregate because of 2 kg/dm^3 $<\rho<3$ kg/dm^3.

4.1.2 Recycled concrete aggregate taken from Berlin

RCA was supplied from demolition of waste water treatment plant which was built on 19th century. Average compressive strength of concrete of this building was about 36 MPa.

RCA was prepared for two different sizes at recycling plant. These sizes were 2-8 mm and 8-16 mm. In the concrete mixtures 0-2 mm was used only from NA. RCA was shown in Figure 4.19 and Figure 4.20.

Figure 4.19 : RCA Berlin (8-16 mm in size).

Figure 4.20 : RCA Berlin (2-8 mm in size).

4.1.2.1 Sieve Analysis

Sieve analysis was done for each group of RCA three times. Sieves were shown in Figure 4.14. 4000 grams of materials were taken for the sieve analysis each time. The first group was sieved in the sieve opening from 8 mm to 0 mm and the second group was sieved in the sieve opening from 16 mm to 0 mm. Sieve analysis results of the first group of RCA were shown in Table 4.12, Table 4.13 and Table 4.14. Sieve analysis results of the second group of RCA were shown in Table 4.15, Table 4.16 and Table 4.17.

For the first sieve analysis of RCA (2-8): k = 4,63.
For the second sieve analysis of RCA (2-8): k = 4,60.
For the third sieve analysis of RCA (2-8): k = 4,57.
For the first sieve analysis of RCA (8-16): k = 5,85.
For the second sieve analysis of RCA (8-16): k = 5,86.
For the third sieve analysis of RCA (8-16): k = 5,88.

Table 4.12 : First sieve analysis of RCA Berlin (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	55,2	3944,8	1,38	1,38	98,62
4	2509,2	1435,6	62,73	64,11	35,89
2	1386	49,6	34,65	98,76	1,24
1	23,2	26,4	0,58	99,34	0,66
0,5	4,8	21,6	0,12	99,46	0,54
0,25	4,4	17,2	0,11	99,57	0,43
0,125	4,4	12,8	0,11	99,68	0,32
0,063	6	6,8	0,15	99,83	0,17
0	6,8	0	0,17	100	0

Table 4.13 : Second sieve analysis of RCA Berlin (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	60,8	3939,2	1,52	1,52	98,48
4	2 84	1555,2	59,6	61,12	38,88
2	1509,6	45,6	37,74	98,86	1,14
1	20	25,6	0,5	99,36	0,64
0,5	4,4	21,2	0,11	99,47	0,53
0,25	3,6	17,6	0,09	99,56	0,44
0,125	3,6	14	0,09	99,65	0,35
0,063	6,8	7,2	0,17	99,82	0,18
0	7,2	0	0,18	100	0

Table 4.14 : Third sieve analysis of RCA Berlin (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	58,4	3941,6	1,46	1,46	98,54
4	2245,2	1696,4	56,13	57,59	42,41
2	1656,8	39,6	41,42	99,01	0,99
1	17,6	22	0,44	99,45	0,55
0,5	4,4	17,6	0,11	99,56	0,44
0,25	3,2	14,4	0,08	99,64	0,36
0,125	3,6	10,8	0,09	99,73	0,27
0,063	5,2	5,6	0,13	99,86	0,14
0	5,6	0	0,14	100	0

Table 4.15 : First sieve analysis of RCA Berlin (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	135,2	3864,8	3,38	3,38	96,62
8	3437,2	427,6	85,93	89,31	10,69
4	352,8	74,8	8,82	98,13	1,87
2	12,8	62,0	0,32	98,45	1,55
1	6,0	56,0	0,15	98,60	1,40
0,5	5,6	50,4	0,14	98,74	1,26
0,25	4,8	45,6	0,12	98,86	1,14
0,125	10,8	34,8	0,27	99,13	0,87
0,063	12,0	22,8	0,3	99,43	0,57
0	22,8	0	0,57	100	0

Table 4.16 : Second sieve analysis of RCA Berlin (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	73,6	3926,4	1,84	1,84	98,16
8	3562,8	363,6	89,07	90,91	9,09
4	298,4	65,2	7,46	98,37	1,63
2	7,6	57,6	0,19	98,56	1,44
1	2,8	54,8	0,07	98,63	1,37
0,5	2,8	52,0	0,07	98,70	1,30
0,25	4,4	47,6	0,11	98,81	1,19
0,125	10,0	37,6	0,25	99,06	0,94
0,063	14,0	23,6	0,35	99,41	0,59
0	23,6	0	0,59	100	0

Table 4.17 : Third sieve analysis of RCA Berlin (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	1041	3895,9	2,6	2,6	97,4
8	3564,3	331,6	89,11	91,71	8,29
4	276,4	55,2	6,91	98,62	1,38
2	4,7	50,5	0,12	98,74	1,26
1	0,8	49,7	0,02	98,76	1,24
0,5	2,5	47,2	0,06	98,82	1,18
0,25	3,7	43,5	0,09	98,91	1,09
0,125	8,7	34,8	0,22	99,13	0,87
0,063	11,3	23,5	0,28	99,41	0,59
0	23,5	0	0,59	100	0

Aggregate grading curves for RCA from Berlin size between 2 and 8 mm were shown in Figure 4,21 and 8 and 16 mm were shown in Figure 4,22. k(avg) = 4,60 for RCA (2-8 mm) and k(avg) = 5,86 RCA (8-16 mm) were obtained.

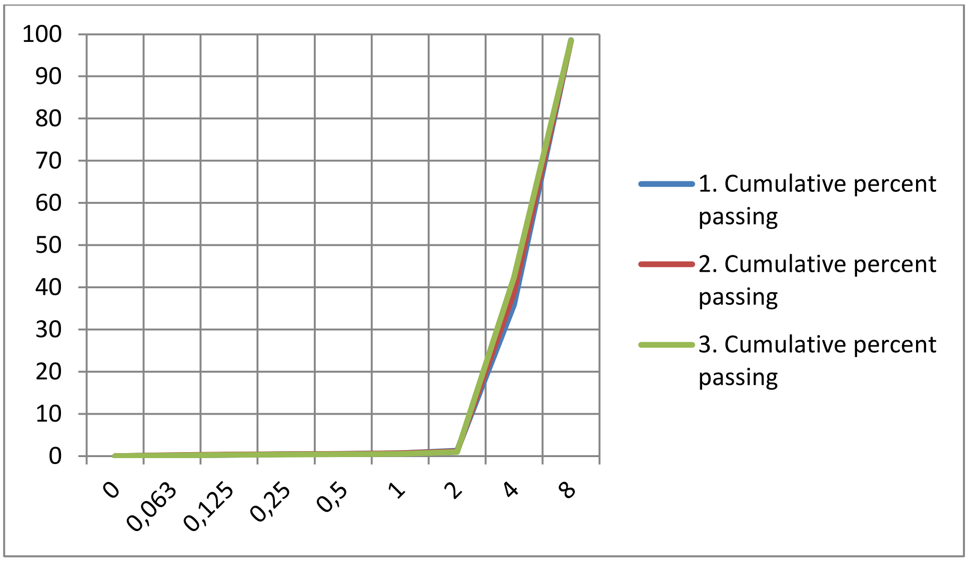


Figure 4.21 : Aggregate grading curves for RCA (2-8 mm).

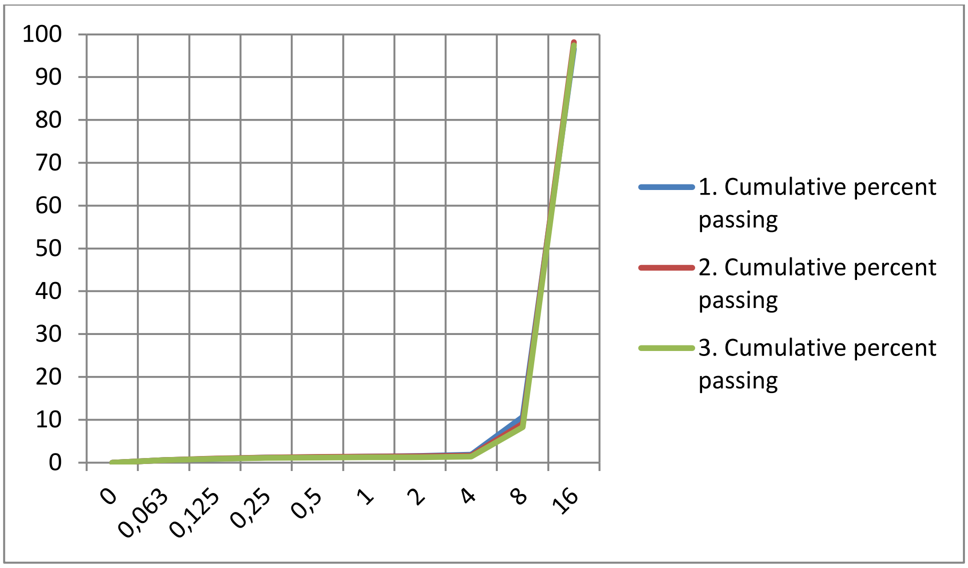


Figure 4.22 : Aggregate grading curves for RCA Berlin (8-16 mm).

4.1.2.2 Pycnometer

In order to determine the density of RCA pycnometer analysis were done according to DIN 1097-6. The same procedure was applied to RCA taken from Berlin, which was applied to RCA taken from Istanbul to determine the density of the aggregate. Pycknometers were shown in Figure 4.18.

For RCA (2-8 mm in size): ρ = 2,6 kg / dm³.
For RCA (8-16 mm in size): ρ = 2,57 kg / dm³.

According to DIN EN 1097-6, RCA taken from Berlin is normal aggregate because of 2 kg/dm³ <ρ<3 kg/dm³.

3.1.3 Natural aggregate

In this study, size of NA used were 0-2 mm, 2-8 mm, 8-16 mm were . NA supplied from Berlin was shown in Figure 4.23, Figure 4.24 and Figure 4.25.

Figure 4.23 : NA (8-16 mm in size).

Figure 4.24 : NA (2-8 mm in size).

Figure 4.25 : NA (0-2 mm in size).

4.1.3.1 Sieve analysis

Sieve analysis was done for each group of NA. Sieves were shown in Figure 4.14. 5000 grams of NA were sieved to determine the aggregate grading curve. Sieve analysis results of NA were shown in Table 4.18, Table 4.19, Table 4.20 for 0-2 mm; Table 4.21, Table 4.22, Table 4.23 for 2-8 mm; Table 4.24, Table 4.25 and Table 4.26 for 8-16 mm.

For the first sieve analysis of RCA (0-2 mm): k = 1,61.
For the second sieve analysis of RCA (0-2 mm): k = 1,65.
For the third sieve analysis of RCA (0-2 mm): k = 1,62.
For the first sieve analysis of RCA (2-8): k = 4,68.
For the second sieve analysis of RCA (2-8): k = 4,68.
For the third sieve analysis of RCA (2-8): k = 4,76.
For the first sieve analysis of RCA(8-16): k = 5,99.
For the second sieve analysis of RCA (8-16): k = 5,96.
For the third sieve analysis of RCA (8-16): k = 6,04.

Table 4.18 : First sieve analysis of NA (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
2	136,6	4863,4	2,73	2,73	97,27
1	587,3	4276,1	11,75	14,48	85,52
0,5	1740,2	2535,9	34,8	49,28	50,72
0,25	2249,3	286,6	44,99	94,27	5,73
0,125	259,9	26,7	5,2	99,47	0,53
0,063	16,5	10,2	0,33	99,8	0,2
0	10,2	0	0,2	100	0

Table 4.19 : Second sieve analysis of NA (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
2	132,1	4867,9	2,64	2,64	97,36
1	633,9	4234	12,68	15,32	84,68
0,5	1807,7	2426,3	36,15	51,47	48,53
0,25	2184	242,3	43,68	95,15	4,85
0,125	225,3	17	4,51	99,66	0,34
0,063	14,1	2,9	0,28	99,94	0,06
0	2,9	0	0,06	100	0

Table 4.20 : Third sieve analysis of NA (0-2 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
2	127,8	4872,2	2,56	2,56	97,44
1	606,3	4265,9	12,13	14,68	85,32
0,5	1780,9	2485	35,62	50,3	49,7
0,25	2208,1	276,9	44,16	94,46	5,54
0,125	248,3	28,6	4,97	99,43	0,57
0,063	19,7	8,9	0,39	99,82	0,18
0	8,9	0	0,18	100	0

Table 4.21 : First sieve analysis of NA (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	4,9	4925,1	1,5	1,5	98,5
4	3365,3	1559,8	67,31	68,8	31,2
2	1505,2	54,6	30,1	98,91	1,09
1	27,5	27,1	0,55	99,46	0,54
0,5	5,7	21,4	0,11	99,57	0,43
0,25	5	16,4	0,1	99,67	0,33
0,125	4,9	11,5	0,1	99,77	0,23
0	11,5	0	0,23	100	0

Table 4.22 : Second sieve analysis of NA (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	76,4	4923,6	1,53	1,53	98,47
4	3370,2	1553,4	67,4	68,93	31,07
2	1510,3	43,1	30,21	99,14	0,86
1	21	22,1	0,42	99,56	0,44
0,5	3,4	18,7	0,07	99,63	0,37
0,25	3,6	15,1	0,07	99,7	0,3
0,125	4,3	10,8	0,09	99,78	0,22
0	10,8	0	0,22	100	0

Table 4.23 : Third sieve analysis of NA (2-8 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
8	86,3	4913,7	1,73	1,73	98,27
4	3698	1215,7	73,96	75,69	24,31
2	1181,3	34,4	23,63	99,31	0,69
1	13,5	20,9	0,27	99,58	0,42
0,5	3,5	17,4	0,07	99,65	0,35
0,25	3,9	13,5	0,08	99,73	0,27
0,125	4,2	9,3	0,08	99,81	0,19
0	9,3	0	0,19	100	0

Table 4.24 : First sieve analysis of NA (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	322,6	4677,4	6,45	6,45	93,55
8	4346,6	330,8	86,93	93,38	6,62
4	316,5	14,3	6,33	99,71	0,29
2	3,5	10,8	0,07	99,78	0,22
1	1,2	9,6	0,02	99,81	0,19
0,5	1,1	8,5	0,02	99,83	0,17
0,25	1,4	7,1	0, 3	99,86	0,14
0,125	1,8	5,3	0,04	99,89	0,11
0	5,3	0	0,11	100	0

Table 4.25 : Second sieve analysis of NA (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	205,7	4749,3	4,41	4,11	95,89
8	4442,6	351,7	88,85	92,97	7,03
4	333,9	17,8	6,68	99,64	0,36
2	5,3	12,5	0,11	99,75	0,25
1	2	10,5	0,04	99,79	0,21
0,5	1,7	8,8	0,03	99,82	0,18
0,25	1,6	7,2	0,03	99,86	0,14
0,125	2,3	4,9	0,05	99,9	0,1
0	4,9	0	0,10	100	0

Table 4.26 : Third sieve analysis of NA (8-16 mm).

Sieve size (mm)	Retained (g)	∑ Passing (g)	Retained (%)	∑ Retained (%)	∑ Passing (%)
16	471,8	4528,2	9,44	9,44	90,56
8	4329,7	198,5	86,59	96,03	3,97
4	186	12,5	3,72	99,75	0,25
2	1,2	11,3	0,02	99,77	0,23
1	0,4	10,9	0,01	99,78	0,22
0,5	0,7	10,2	0,01	99,8	0,2
0,25	1,3	8,9	0,03	99,82	0,18
0,125	2,5	6,4	0,05	99,87	0,13
0	6,4	0	0,13	100	0

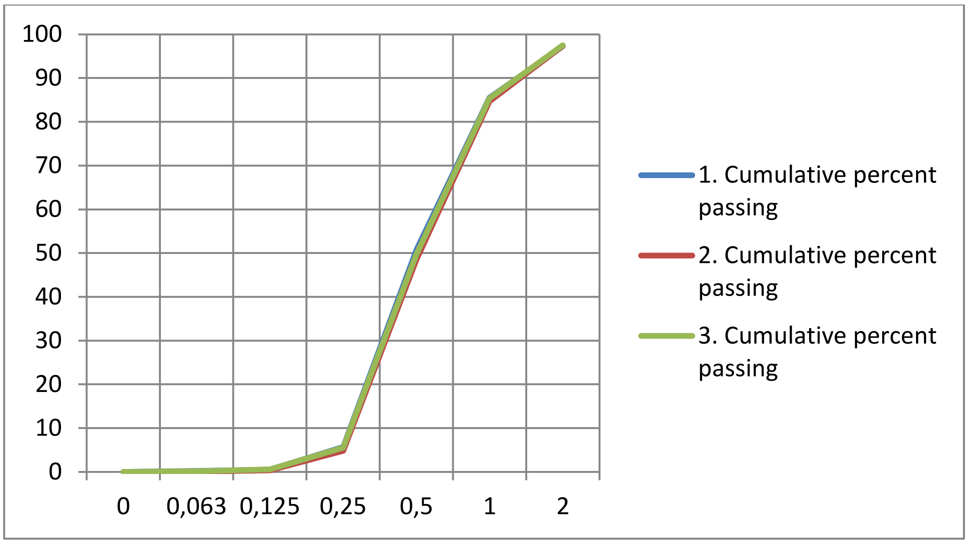


Figure 4.26 : Aggregate grading curves for NA (0-2 mm).

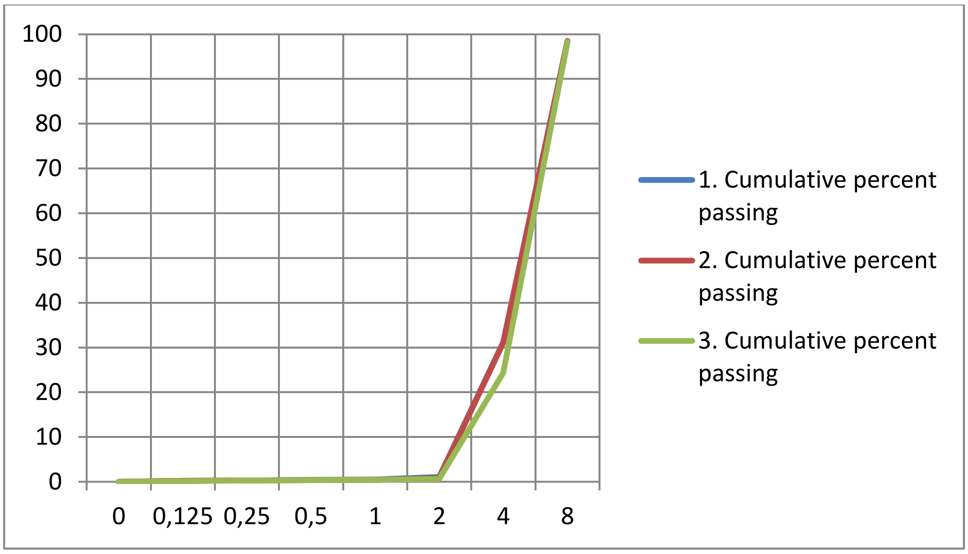


Figure 4.27 : Aggregate grading curves for NA (2-8 mm).

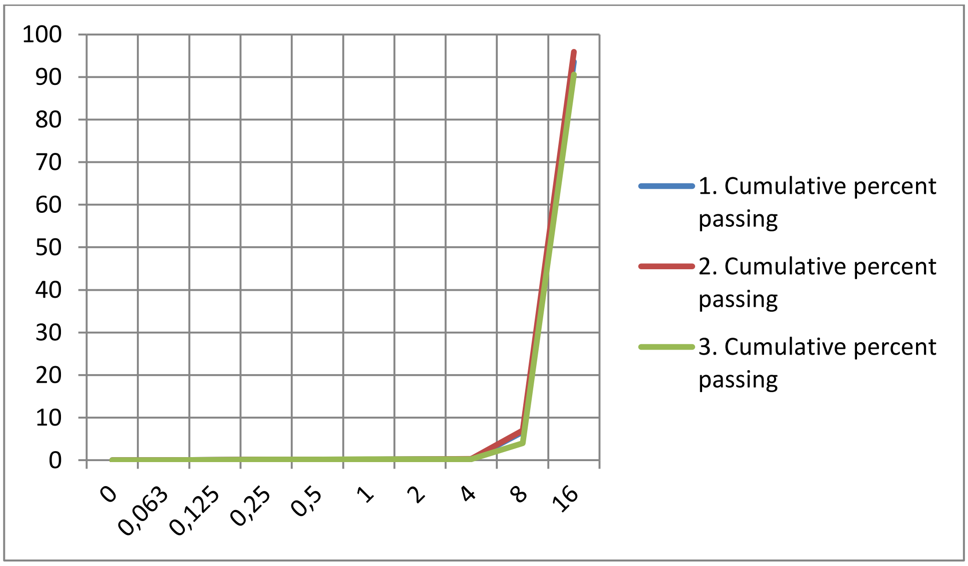


Figure 4.28 : Aggregate grading curves for NA (8-16 mm).

Aggregate grading curves for NA size between 0 and 2 mm were shown in Figure 4.26, 2 and 8 mm were shown in Figure 4.27 and 8 and 16 mm were shown in Figure 4.28. k(avg) = 1,62 for NA (0-2 mm), k(avg) = 4,71 for NA (2-8 mm) and k(avg) = 6 NA (8-16 mm) were obtained.

4.1.3.2 Pycnometer

In order to determine the density of NA pycnometer analysis was done according to DIN 1097-6. Pycknometers were shown in Figure 4.18.

For NA (0-2 mm in size): $\rho = 2{,}6$ kg / dm^3.
For NA (2-8 mm in size): $\rho = 2{,}6$ kg / dm^3.
For NA (8-16 mm in size): $\rho = 2{,}6$ kg / dm^3.

According to DIN EN 1097-6, NA is normal aggregate because of 2 kg/dm^3 $<\rho<$3 kg/dm^3.

4.1.4 Water

Drinkable tap water was used in all experiments.

4.1.5 Cement

For this study, CEM II/B-M (S-LL) 42,5 N type Portland composite cement in accordance with DIN EN 197-1 [47] was used. N code symbolizes normal early strength, M code symbolizes several additives like blast-furnace slag (code S) and limestone (code LL) amounting to a total of 21–35% (code B). This cement has 65 – 79% clinker.

Density of the cement is : $\rho = 3$ kg / dm^3. Standard 28 days strength of the cement is between 42.5 and 62.5 MPa. Early 2 days strength of cement is minimum 10 MPa.

4.1.6 Microsilica

Microsilica Grade 940 U was used. Density of the microsilica is: $\rho = 2{,}4$ kg / dm^3. Microsilica used in experimental study is dry silica fume. Maximum chloride content is 0.1% M. It provides the conditions of DIN EN 13263-1[48].

4.1.7 Superplasticizer

ADVA Flow 342 (BV_FM) superplasticizer (FM) was used that had high plasticizing effect. Density of the plasticizer is : $\rho = 1.08 \pm 0.02$ kg/dm^3. Maximum chloride content is 0.1% M. It provides the conditions of DIN EN 934-2 [49].

4.2 Concrete Mixture Proportion

Determining of **c**oncrete mixture proportion it was planned to have fallowing ratios: aggregate took up 68%, water took up 10%, cement took up 20%, air took up 1,5% of the total volume of concrete. For the calculations of concrete mixture proportion, Formula **(4.2)** was used. Calculations were done for 1000 liters volume.

$$1000 = \frac{z}{\rho_z} + \frac{f}{\rho_f} + \frac{w}{\rho_w} + \frac{g}{\rho_g} + p \quad [dm^3/m^3] \tag{4.2}$$

In this formula:

z: Quantity of cement [kg/m^3]
ρ_z: Density of cement [kg/dm^3]
f: Quantity of microsilica [kg/m^3]
ρ_f: Density of microsilica [kg/dm^3]
w: Quantity of water [kg/m^3]
ρ_w: Density of water [kg/dm^3]
g: Quantity of aggregate (RCA from Berlin, RCA from Istanbul and NA) [kg/m^3]
ρ_g: Density of aggregate (RCA from Berlin, RCA from Istanbul and NA) [kg/dm^3]
p: Volume of air [dm^3/m^3]

p was accepted 1,5% in the concrete mixture. Hence, for 1000 liters of concrete; p = 1000 x 1,5/100 = 15 liters

In order to determine aggregate proportion in concrete Figure 4.29 was used for the concrete made with RCA from Istanbul and Figure 4.30 was used for the concrete made with RCA Berlin. Aggregate grading curve was chosen between A32 and B32 ideal lines for the concrete made with RCA from Istanbul and aggregate grading curve was chosen between A16 and B16 ideal lines for the concrete made with RCA from Berlin.

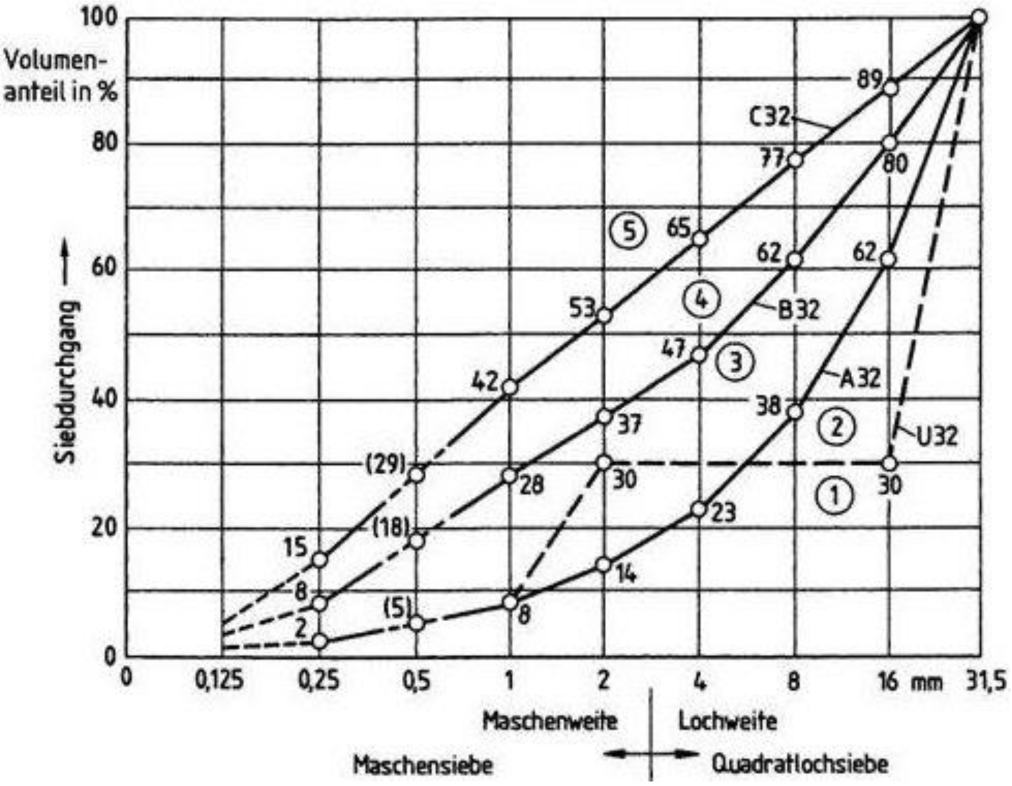


Figure 4.29 : A32, B32, C32 ideal aggregate grading curves.

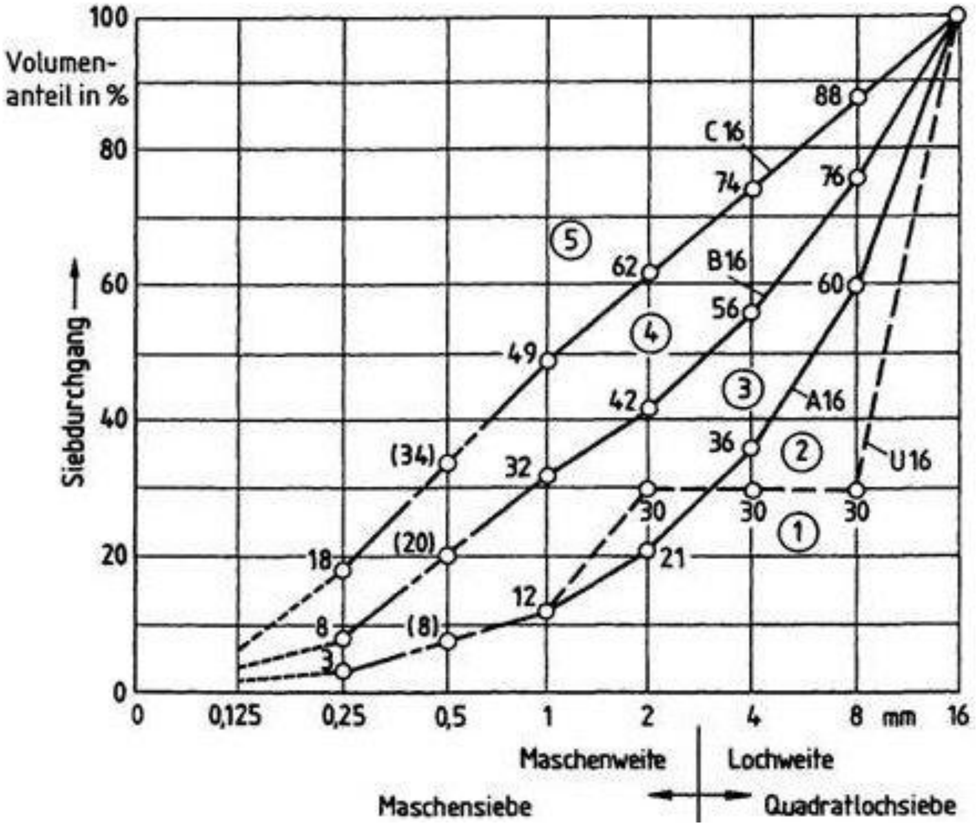


Figure 4.30 : A16, B16, C16 ideal aggregate grading curves.

In order to determine of w/z ratio Figure 4.31[50] was used.

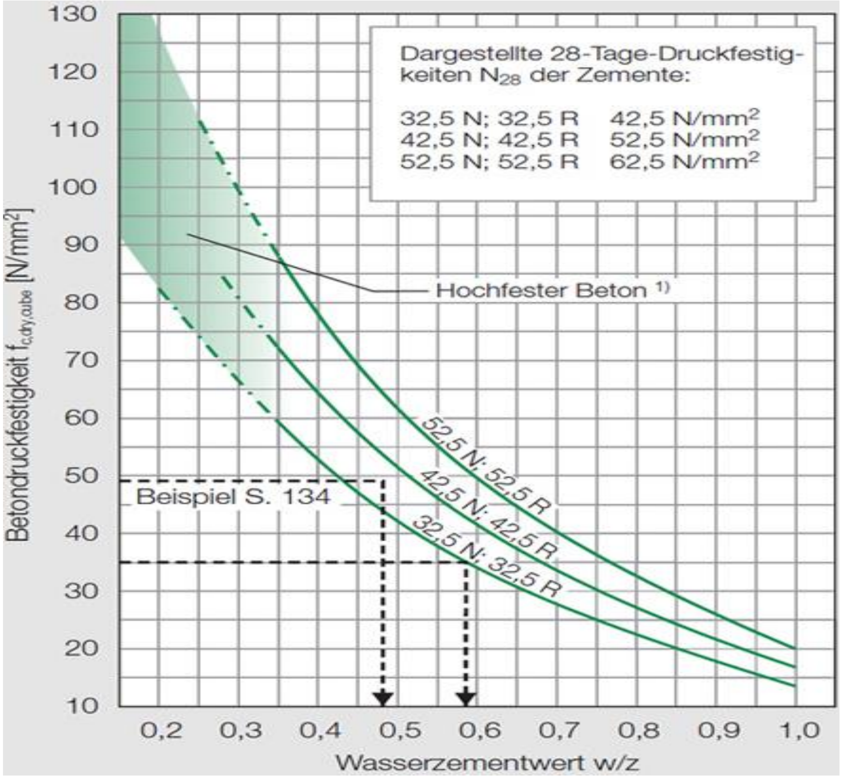
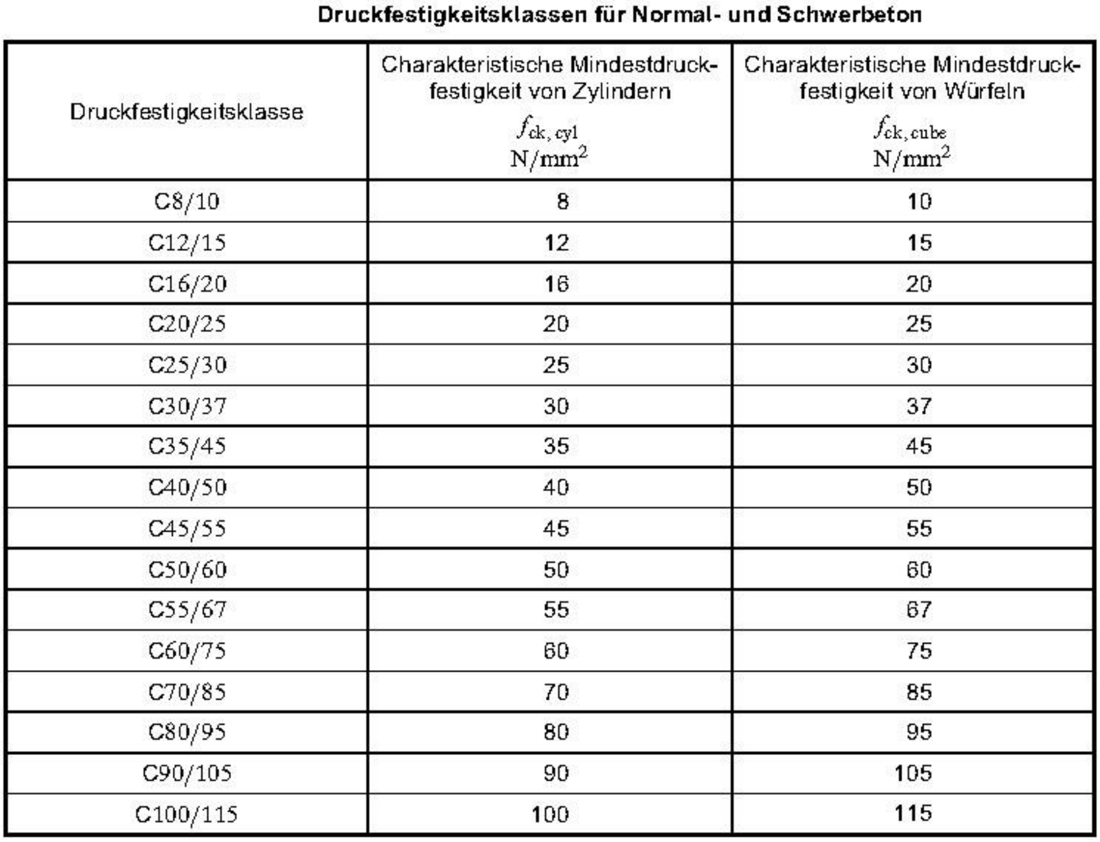


Figure 4.31 : Compressive strength versus w/z ratio according to cement type.

To obtain C35/45 compressive strength class with using high content of RCA concrete mixture propotion was calculated. Because of this reason, concrete was made by using 50%, 75% and 100% RCA. Compressive strength classes for normal concrete according to DIN EN 206-1 was shown in Figure 4.32.

According to Figure 4.32, for C35/45:

fcm,cube = fck + 8 N/mm²
fcm,cube ≥ 45 + 8 = 53 N/mm²



Druckfestigkeitsklassen für Normal- und Schwerbeton

Druckfestigkeitsklasse	Charakteristische Mindestdruckfestigkeit von Zylindern $f_{ck,cyl}$ N/mm^2	Charakteristische Mindestdruckfestigkeit von Würfeln $f_{ck,cube}$ N/mm^2
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Figure 4.32 : Compressive strength classes for normal and heavy concrete.

4.2.1 Mixture with 20% RCA

Microsilica was 10% and superplasticizer (FM) was 1% of cement quantity.

4.2.1.1 RCA Istanbul

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,35

z = 420 kg

f = 40 kg

w = 147 kg

0/2 RCA = 42 kg (35% of total RCA in the mixture)

2/8 RCA = 26,67 kg (22% of total RCA in the mixture)

8/22 RCA = 50,67 kg (42% of total RCA in the mixture)

0/2 NA = 586,67 kg (35% of total RCA in the mixture)

2/8 NA = 380 kg (23% of total RCA in the mixture)

8/16 NA = 713,33 kg (42% of total RCA in the mixture)

FM = 4,2 kg

4.2.1.2 RCA Berlin

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,35
z = 420 kg
f = 40 kg
w = 147 kg
2/8 RCA = 40,50 kg (35% of total RCA in the mixture)
8/16 RCA = 76,50 kg (65% of total RCA in the mixture)
0/2 NA = 630,00 kg (37% of total NA in the mixture)
2/8 NA = 365 kg (22% of total NA in the mixture)
8/16 NA = 688,33 kg (41% of total NA in the mixture)
FM = 4,2 kg

4.2.2 Mixture with 50% RCA

Microsilica was 10% of and FM was 1,5 % of cement quantity.

4.2.2.1 RCA Istanbul

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,35
z = 420 kg
f = 40 kg
w = 147 kg
0/2 RCA = 315 kg (35% of total RCA in the mixture)
2/8 RCA = 203,33 kg (23% of total RCA in the mixture)
8/22 RCA = 383,33 kg (43% of total RCA in the mixture)
0/2 NA = 315,00 kg (35% of total NA in the mixture)
2/8 NA = 203,33 kg (23% of total NA in the mixture)
8/16 NA = 383,33 kg (43% of total NA in the mixture)
FM = 6,3 kg

During the experiment concrete needed 50 kg water. After adding 50 kg water to concrete, new water quantity and w/z ratio were:

w =147+50 = 197 kg
w/z = 197/420 = 0,47

4.2.2.2 RCA Berlin

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,35
z = 420 kg
f = 40 kg
w = 147 kg
2/8 RCA = 303,33 kg (35% of total RCA in the mixture)
8/16 RCA = 573,33 kg (65% of total RCA in the mixture)
0/2 NA = 630 kg (68% of total NA in the mixture)
2/8 NA = 101,67 kg (11% of total NA in the mixture)
8/16 NA = 191,67 kg (21% of total NA in the mixture)
FM = 6,3 kg

During the experiment concrete needed 33,33 kg water. After adding 33,33 kg water to concrete, new water quantity and w/z ratio were:

w =147+33,33 = 180,33 kg
w/z = 197/420 = 0,43

4.2.3. Mixture with 50% RCA (new mixture)

Water/cement ratio was obtained from the previous experiment. Microsilica was 10% and FM was 1 % of cement quantity.

4.2.3.1 RCA Istanbul

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,47
z = 397 kg
f = 38 kg
w = 186 kg
0/2 RCA = 298 kg (35% of total RCA in the mixture)
2/8 RCA = 192 kg (22% of total RCA in the mixture)
8/16 RCA = 364 kg (43% of total RCA in the mixture)
0/2 NA = 302 kg (35% of total NA in the mixture)
2/8 NA = 192 kg (22% of total NA in the mixture)

8/16 NA = 363 kg (42% of total NA in the mixture)
FM = 3,97 kg

4.2.3.2 RCA Berlin

For 1000 liters of concrete, the concrete mixture had:

w/z = 0,43
z = 397 kg
f = 38 kg
w = 173 kg
2/8 RCA = 310 kg (37% of total RCA in the mixture)
8/16 RCA = 531 kg (63% of total RCA in the mixture)
0/2 NA = 574 kg (62% of total NA in the mixture)
2/8 NA = 120 kg (13% of total NA in the mixture)
8/16 NA = 226 kg (25% of total NA in the mixture)
FM = 3,97 kg

4.2.4 Mixture with 75% RCA

Water/cement ratio was estimated by using previous results of the experiments. Microsilica was 10% and FM was 2% of cement quantity.

4.2.4.1 RCA Istanbul

For 1000 liters of concrete, the concrete mixture had:

w/z = 0,48
z = 397 kg
f = 38 kg
w = 189,46 kg
0/2 RCA = 440,2 kg (35% of total RCA in the mixture)
2/8 RCA = 293,2 kg (22% of total RCA in the mixture)
8/16 RCA = 533,25 kg (42% of total RCA in the mixture)
0/2 NA = 146,7 kg (35% of total NA in the mixture)
2/8 NA = 97,75 kg (23% of total NA in the mixture)
8/16 NA = 177,75 kg (42% of total NA in the mixture)
FM = 7,94 kg

During the experiment concrete needed 13,15 kg water. After adding 13,15 kg water to concrete, new water quantity and w/z ratio were:

w = 13,15 + 189,46 = 202,61 kg
w/z = 202,61/ 397 = 0,51

4.2.4.2 RCA Berlin

For 1000 liters of concrete, the concrete mixture had:

w/z = 0,49
z = 397 kg
f = 38 kg
w = 195,9 kg
2/8 RCA = 322,5 kg (35% of total RCA in the mixture)
8/16 RCA = 570,7 kg (65% of total RCA in the mixture)
0/2 NA = 514 kg (37% of total NA in the mixture)
2/8 NA = 107,5 kg (22% of total NA in the mixture)
8/16 NA = 190,2 kg (41% of total NA in the mixture)
FM = 7,94 kg

4.2.5 Mixture with 100% RCA

The same water/cement ratio of concrete made with 50% RCA was used here. Microsilica was 10% and FM was 1,5 % of cement quantity.

4.2.5.1 RCA Istanbul

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,47
z = 397 kg
f = 38 kg
w = 186 kg
0/2 RC = 587 kg (35% of total RCA in the mixture)
2/8 RC = 391 kg (23% of total RCA in the mixture)
8/22 RC = 711 kg (42% of total RCA in the mixture)
FM = 6,3 kg

During the experiment concrete needed 180 kg water. After adding 180 kg water to concrete, new water quantity and w/z ratio were:

w = 186 + 180 = 366 kg
w/z = 366/ 397 = 0,92

4.2.5.2 RCA Berlin

For 1000 liters of concrete, the concrete mixture had:

w/z= 0,43
z = 397 kg
f = 38 kg
w = 173 kg
0/2 NA = 574 kg (33% of total aggregate in the mixture)
2/8 RC = 430 kg (24% of total aggregate in the mixture)
8/16 RC = 761kg (43% of total aggregate in the mixture)
FM = 6,3 kg

During the experiment concrete needed 123,33 kg water. After adding 123,33 kg water to concrete, new water quantity and w/z ratio were:

w = 173 + 123,33 = 296,33 kg
w/z = 296,33/397 = 0,75

4.3 Experiments

4.3.1 Flow table test

Flow table test on fresh concrete was completed according to DIN EN 12350-5 [51]. The cone was located in the center of the flow table and filled with fresh concrete. Then, the flow table was dropped 25 times. After that, the diameter of consolidating of concrete on the flow table was measured. The flow table was shown in Figure 4.33. Process of flow table test was shown in Figure 4.34 and Figure 4.35.

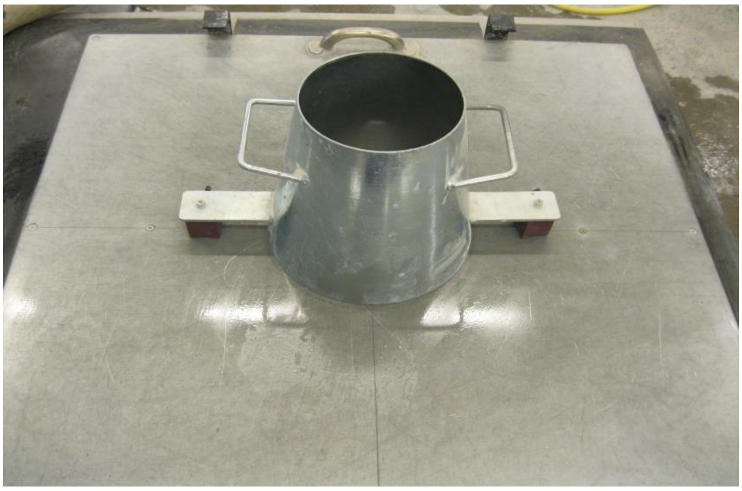
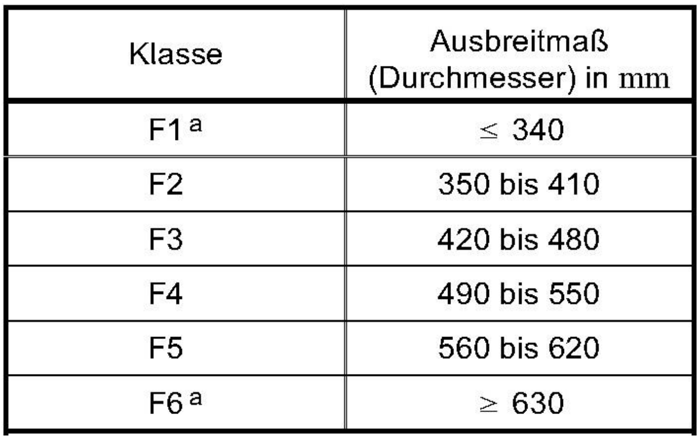


Figure 4.33 : The flow table.

Figure 4.34 : Concrete right after cone was removed.

Figure 4.35 : Concrete after the flow table was dropped 25 times.

Consolidating classes according to DIN EN 206-1 was shown in Figure 4.36. According DIN EN 206-1, if consolidating of fresh concrete is equal or smaller than 340 mm consolidating class is F1, if consolidating of fresh concrete is between 350 and 410 mm consolidating class is F2, if consolidating of fresh concrete is between 420 and 480 mm consolidating class is F3, if consolidating of fresh concrete is between 490 and 550 mm consolidating class is F4, if consolidating of fresh concrete is between 560 and 620 mm consolidating class is F5 and if consolidating of fresh concrete is equal or bigger than 630 mm consolidating class is F6.



Klasse	Ausbreitmaß (Durchmesser) in mm
F1 [a]	≤ 340
F2	350 bis 410
F3	420 bis 480
F4	490 bis 550
F5	560 bis 620
F6 [a]	≥ 630

Figure 4.36 : Consolidating classes.

4.3.2 Compressive strength test

In order to test the compressive strength and understand the behavior of concrete made with different mixture proportion of RCA, the concrete cube moulds were filled with concrete of different mixture proportions. The length of the cubes was 15 cm.

The compressive strength test was carried out according to German Standard DIN 1048 on concrete specimens of size 150x150x150 mm and at the age of 28 days.

All materials used in concrete mixture were weighted separately before making the concrete. Then coarse aggregates, fine aggregates, cement, microsilica, Superplasticizer and water were put in the concrete mixer with this order. After all the materials were added in the concrete mixer, it was waited until the mixture was uniform. Concrete mixer was shown in Figure 4.37. Workability of concrete was checked. Concrete in the concrete mixer was shown in Figure 4.38. Extra water was added to the concrete mixture when if it was needed so then water was added in the concrete mixtures made with 50% RCA, 75% RCA and 100% RCA.

Figure 4.37 : The concrete mixer.

Figure 4.38 : Concrete in the concrete mixer.

The fresh concrete was poured in the concrete cube moulds had 15 cm long. The cubes were fixed on the vibrating table and filled with concrete up to about 60% of the volume without vibration. The remaining concrete was poured in the cubes on the vibrating table until they were filled with concrete under vibration condition. The table was vibrated in frequency of 75 Hz for 60 s. Concrete vibration table was shown in Figure 4.39. Fresh concrete in the concrete cube moulds was shown in Figure 4.40. Fresh concrete in the concrete cube moulds covered by plastic bag during a day were shown in Figure 4.41. After that concrete cube moulds were removed around the hardened concrete specimens and then the specimens were put in curing tank for 28 days. Specimens in the curing tank that were gained the required strengths without any dehydration were shown in Figure 4.42.

Figure 4.39 : The vibrating table.

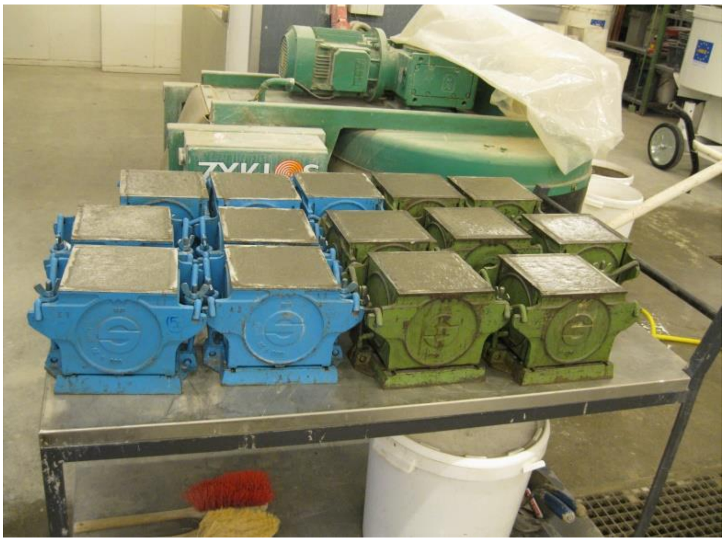


Figure 4.40: The specimens for compressive strength test.

Figure 4.41 : Protection of fresh concrete in the concrete cube moulds.

Figure 4.42 : Curing of the concrete specimens for 28 days.

Concrete cubes were located centrally in the compressive strength test machine in accordance with DIN EN 12390-3 [52]. The compressive strength test machine was shown in Figure 4.43. Upside of the cube was rotated after rotation; it was the side of the cube. After that, load was applied on the specimens and increased continuously until fracture occurred. Maximum load was recorded. Failure of the concrete specimen under compression was shown in Figure 4.44.

Figure 4.43 : The compressive strength test machine.

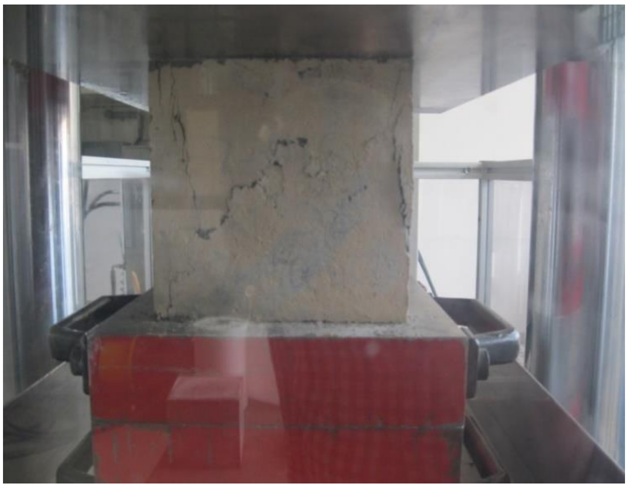


Figure 4.44 : Failure of the concrete specimen under compression.

Compressive strength of concrete cubes was calculated according to DIN EN 12390-3 with Formula **(4.3)**.

$$f_c = F / A_c \tag{4.3}$$

In this formula:

f_c: Compressive strength (MPa or N/mm²)

F : Maximum load (N)

A_c : Surface area of the specimen (mm²)

4.3.3 Determination of chloride content

The determination of chloride (Cl^-) content in RCA and concrete made with RCA was implemented in accordance with DIN EN 1744-1 [53]. For water soluble chloride (Cl^-) determination, sample materials were eluted with ion chromatography, then dried at 105°C, crushed and milled fine analysis in the oscillating disc mill. The content of salts (chloride and sulfate), after one hour of shaking the sample with deionized water and then through a membrane filter of 0,25 microns filtered. Quantification was carried out by the external standard method according to DIN EN 1744-1 [53].

4.3.4 Determination of sulfate content

RCA from Istanbul and RCA from Berlin were tested to find water soluble (SO_4^{2-}) and acid soluble sulfate (SO_3) content. The determination of acid soluble sulfate (SO_3) was implemented in accordance with DIN EN 1744-1 [53] and DIN EN 459-2

[54] and the determination of acid sulfate as SO_3 was implemented in accordance with DIN EN 196-2 [55].

The determination of water soluble sulfate (SO_4^{2-}) content in RCA and concrete made with RCA was implemented with the same method mentioned in section 4.3.3. For acid soluble sulfate (SO_3) determination, 2 mgs of RCA were displaced with dilute hydrochloric acid, digested for approximately 15 minutes, then filtered over a medium pore filter and washed with hot dilute hydrochloric acid. After the adjustment of the pH-value to pH 1, the boiling barium chloride solution was added for the precipitation of the sulfate, and the reaction solution was left over night at approximately 60°C. In the step following this, the barium sulfate precipitation was filtered out and washed chloride free with boiling water. Then the filter with the precipitation was heated to red heat at 925°C ± 25°C until mass stability was reached. The SO_3 content results from the mass of the weight of the red heated residue by means of stoichiometric calculation. Representation of the filtration of the precipated barium sulphate is shown in Figure 4.45.

Figure 4.45 : Representation of the filtration of the precipitated barium sulphate.

4.3.5 Fog chamber and concrete microstructure

Alkali silica reaction (ASR) is a reaction that needs enough alkali (Na, K) in the cement stone, alkaline-sensitive aggregates, enough humidity and reaction time. Development of ASR reaction in concrete was shown in Figure 4.46. Reaction happened between the alkali hydroxides (Na, K & OH) and unstable silica (SiO_2) from aggregate produces gel. The gel absorbed water from the surrounding paste. After absorbing, the gel expands and this internal expansion eventually leads to cracking of the surrounding concrete [56].

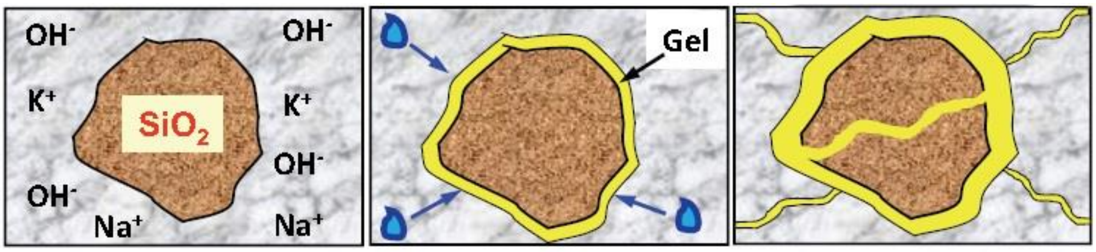


Figure 4.46 : Sequence of ASR in concrete.

A concrete of one to three months age in normal climate does not show a damaging reaction. So concrete specimens of each type (made with 50% RCA, 75% RCA and 100% RCA) were put into the fog chamber (40 °C and 100 % relative humidity) for investigation of ASR. For preparation of concrete specimens, concrete cubes were cut into two pieces and each piece was put into fog chamber. Before the half cubes were put into fog chamber, concrete microstructure was examined at 5 mm and 2 mm length scales.

5. EXPERIMENTAL RESULTS

Compaction of concrete samples were shown in Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4 and Figure 5.5. In Figure 5.1, 5.2 and 5.3 concrete samples made with RCA from Istanbul were on the right hand side, concrete samples made with RCA from Berlin were on the left hand side.

Figure 5.1 : Concrete made with 20 % RCA.

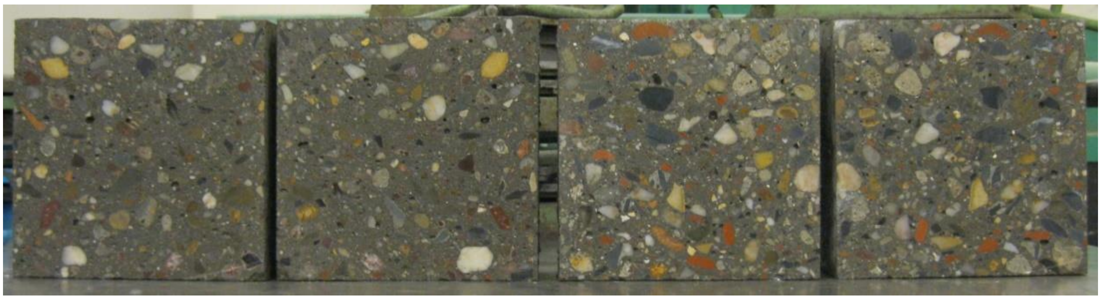


Figure 5.2 : Concrete made with 50 % RCA.

Figure 5.3 : Concrete made with 75% RCA.

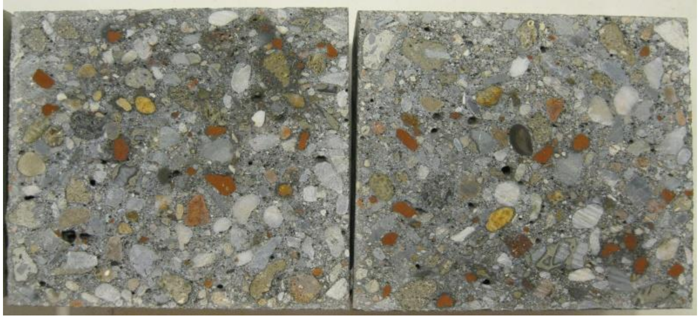


Figure 5.4 : Concrete made with 100% RCA from Istanbul.

Figure 5.5 : Concrete made with 100% RCA from Berlin.

5.1 Flow Table Test

Consolidating classes of concrete made with RCA Berlin and RCA Istanbul according to DIN EN 206-1 were listed: Concrete made from 20 % RCA Berlin and 20% RCA Istanbul were F2. Concrete made with 50% RCA Berlin and 50% RCA Istanbul were F3; concrete made from 50 % RCA Berlin and Istanbul (new mixture) weres F3.Concrete made from 75 % RCA Berlin and Istanbul were F3. Concrete made from 100 % RCA Berlin and Istanbul were F4.

5.2 Compressive Strength

5.2.1 Concrete made with 20% RCA Istanbul

Average compressive strength was 85,25 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 78,43 N/mm².

Table 5.1 : Concrete made with 20% RCA Istanbul.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%20 RCA Istanbul	150	150	150	7,977	1953	86,8
%20 RCA Istanbul	150	150	150	8,405	1883	83,7

5.2.2 Concrete made with 20% RCA Berlin

Average compressive strength was 87,1 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 80,13 N/mm².

Table 5.2 : Concrete made with 20% RCA Berlin.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%20 RCA Berlin	150	150	150	7,935	1939	86,2
%20 RCA Berlin	150	150	150	7,835	1980	88

5.2.3 Concrete made with 50% RCA Istanbul

Average compressive strength was 61,73 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 56,79 N/mm².

Table 5.3 : Concrete made with 50% RCA Istanbul.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%50 RCA Istanbul	150	150	150	7,462	1293	57,5
%50 RCA Istanbul	150	150	150	7,566	1465	65,1
%50 RCA Istanbul	150	150	150	7,543	1410	62,6

5.2.4 Concrete made with 50% RCA Berlin

Average compressive strength was 64,2 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 59,06 N/mm².

Table 5.4 : Concrete made with 50% RCA Berlin.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%50 RCA Berlin	150	150	150	7,445	1435	63,8
%50 RCA Berlin	150	150	150	7,381	1452	64,5
%50 RCA Berlin	150	150	150	7,41	1447	64,3

5.2.5 Concrete made with 50% RCA Istanbul (new mixture)

Average compressive strength was 50,65N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 46,60 N/mm².

Table 5.5 : Concrete made with 50% RCA Istanbul (new mixture).

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%50 RCA Istanbul	150	150	150	7,269	1117	49,7
%50 RCA Istanbul	150	150	150	7,249	1162	51,6
%50 RCA Istanbul	150	150	150	2,251	1138	50,2

5.2.6 Concrete made with 50% RCA Berlin (new mixture)

Average compressive strength was 58,5 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 53,82 N/mm².

Table 5.6 : Concrete made with 50% RCA Berlin (new mixture).

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%50 RCA Berlin	150	150	150	7,41	1369	60,8
%50 RCA Berlin	150	150	150	7,328	1265	56,2
%50 RCA Berlin	150	150	150	7,387	1315	58,5

5.2.7 Concrete made with 75% RCA Istanbul

Average compressive strength was 51,4 N/mm^2 according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 47,29 N/mm^2.

Table 5.7 : Concrete made with 75% RCA Istanbul.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%75 RCA Istanbul	150	150	150	7,312	1122	49,9
%75 RCA Istanbul	150	150	150	7,358	1191	52,9
%75 RCA Istanbul	150	150	150	7,379	1093	48,6
%75 RCA Istanbul	150	150	150	7,154	1111,5	49,4
%75 RCA Istanbul	150	150	150	7,192	1264,5	56,2

5.2.8 Concrete made with 75% RCA Berlin

Average compressive strength was 62,63 N/mm^2 according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 57,62 N/mm^2.

Table 5.8 : Concrete made with 75% RCA Berlin.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%75 RC Berlin	150	150	150	7,32	1426,5	63,4
%75 RC Berlin	150	150	150	7,302	1334,25	59,3
%75 RC Berlin	150	150	150	7,834	1467	65,2

5.2.9 Concrete made with 100% RCA Istanbul

Average compressive strength is 34,8 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength is 32,02 N/mm².

Table 5.9 : Concrete made with 100% RCA Istanbul.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%100 RCA Istanbul	150	150	150	7,136	775	34,4
%100 RCA Istanbul	150	150	150	7,22	797	35,4
%100 RCA Istanbul	150	150	150	7,132	779	34,6

5.2.10 Concrete made with 100% RCA Berlin

Average compressive strength was 51,175 N/mm² according to DIN EN 12390-2. According to previous standard DIN 1054-2, average compressive strength was 47,08 N/mm².

Table 5.10 : Concrete made with 100% RCA Berlin.

Sample Name	L/D (mm)	B (mm)	H (mm)	Mass (kg)	F max (kN)	Compressive Strength (N/mm^2)
%100 RCA Berlin	150	150	150	7,06	1156	51,4
%100 RCA Berlin	150	150	150	7,227	1214	54
%100 RCA Berlin	150	150	150	6,956	966	42,9
%100 RCA Berlin	150	150	150	7,232	1269	56,4

Average compressive strength of concrete made with RCA Istanbul was shown in Table 5.11 and Figure 5.6. Average compressive strength of concrete made with RCA Berlin was shown in Table 5.12 and Figure 5.7.

Table 5.11 : Average compressive strength (concrete made with RCA Istanbul).

Concrete Specimens	Compressive Strength (Mpa)
20% RCA Istanbul	85,25
50% RCA Istanbul	61,73
50% RCA Istanbul (New Mixture)	50,65
75% RCA Istanbul	51,4
100% RCA Istanbul	34,8

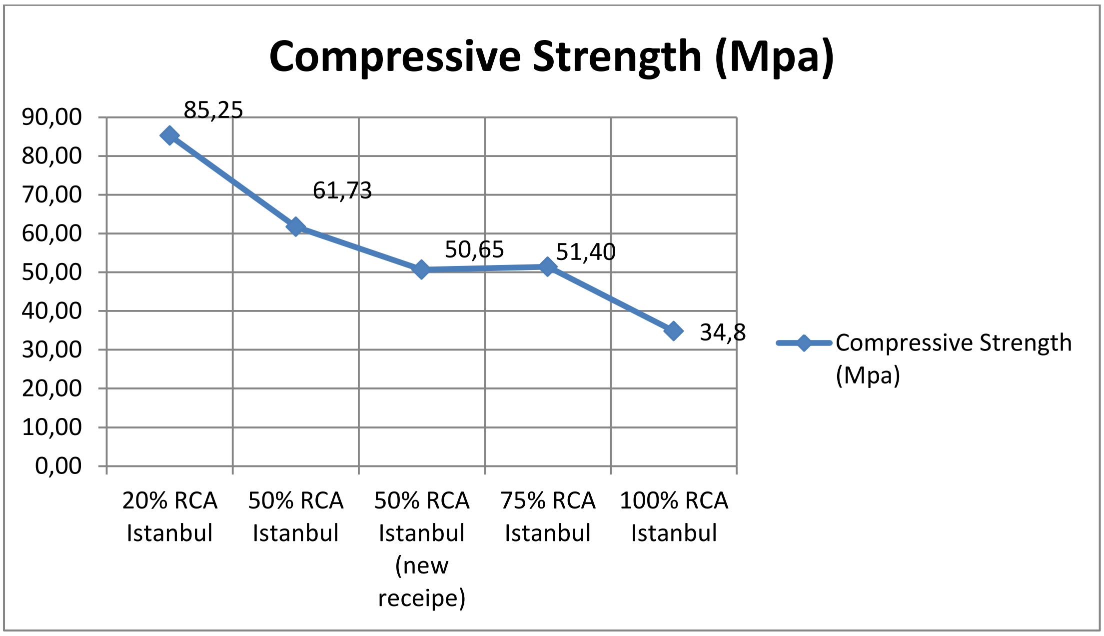


Figure 5.6 : Compressive strength of the concrete made with RCA Istanbul.

Table 5.12 : Average compressive strength (concrete made with RCA Berlin).

Concrete Specimens	Compressive Strength (Mpa)
20% RCA Berlin	87,1
50% RCA Berlin	64,2
50% RC Berlin (New Mixture)	58,5
75% RCA Berlin	62,63
100% RCA Berlin	51,175

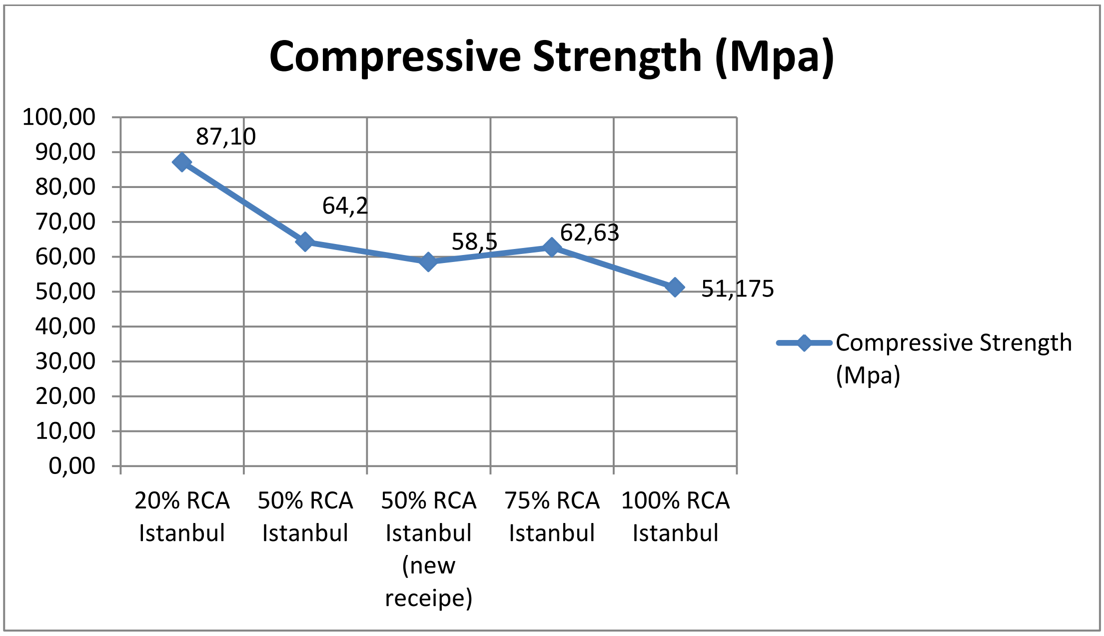


Figure 5.7 : Compressive strength of the concrete made with RCA Berlin.

Comparison of the compressive strength of the concrete made with RCA Berlin and RCA Istanbul was shown in Figure 5.8.

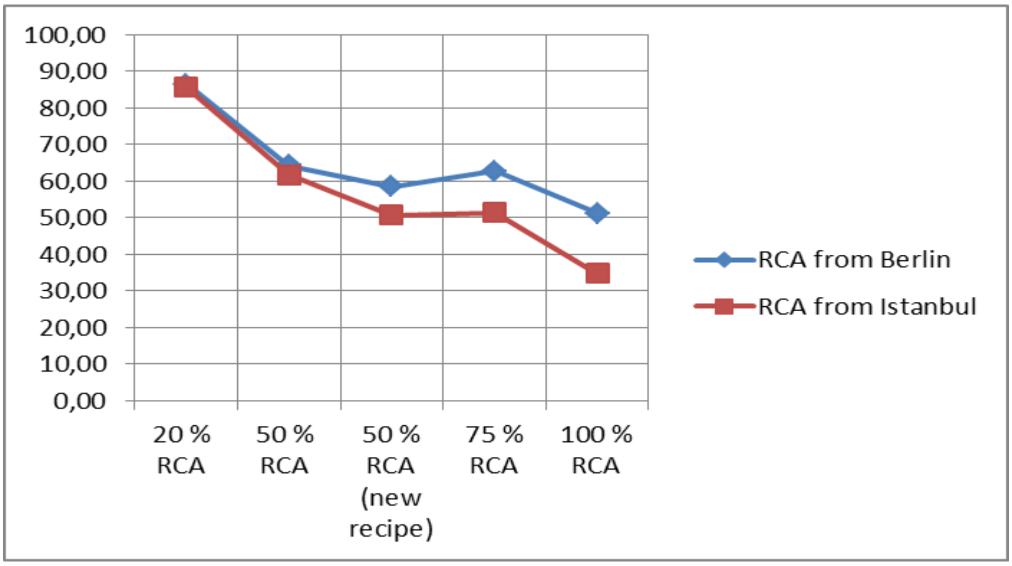


Figure 5.8 : Comparison of the compressive strength test results.

Compressive strength decreased when percentage of RCA in concrete increased. Concrete specimens made with RCA Istanbul had less compressive strength than concrete specimens made with RCA Berlin because concrete made with RCA Istanbul needed more water during concrete production. The more water in concrete means the less compressive strength for concrete.

Table 5.13 : Average density of the concrete specimens.

Concrete Specimens	Density (kg/dm³)
20% RCA Istanbul	2,42
50% RCA Istanbul	2,23
50% RCA Istanbul (new mixture)	2,15
75% RCA Istanbul	2,16
100% RCA Istanbul	2,12
20% RCA Berlin	2,34
50% RCA Berlin	2,20
50% RC Berlin (new mixture)	2,19
75% RCA Berlin	2,22
100% RCA Berlin	2,11

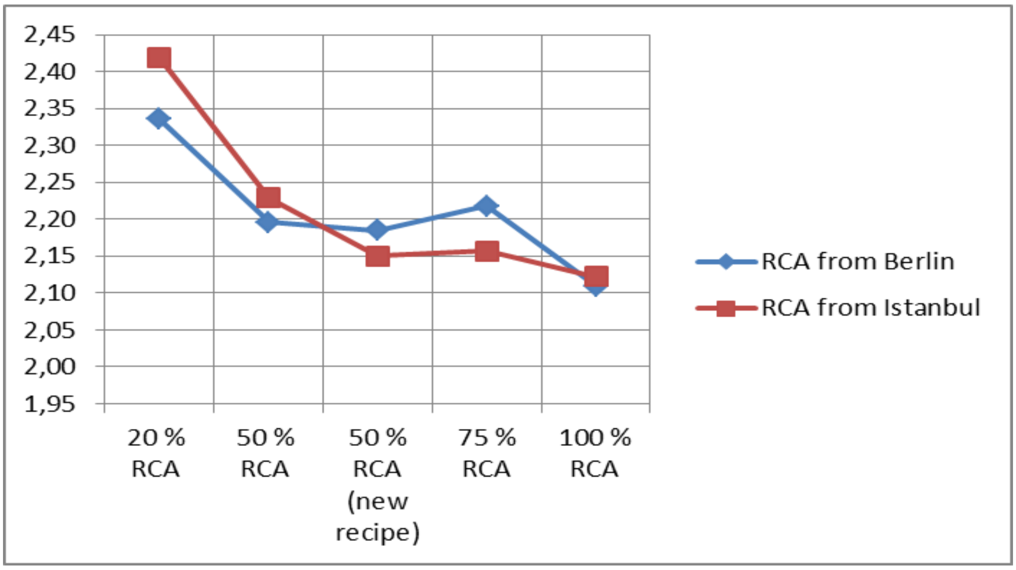


Figure 5.9 : Density comparison of the concrete specimens.

Density of concrete is related with solidity of concrete. Concrete made with RCA had low density. The reasons of the low concrete densities were fineness modulus of aggregate, water absorbion capacity of aggregate, water quantity in concrete, w/z ratio, type of RCA, and etc. Density of concrete made with RCA Istanbul was smaller than RCA Berlin and density of concrete made with RCA Berlin was smaller than NA. Fineness modulus of RCA Istanbul was smaller than RCA Berlin and fineness modulus of RCA Berlin was smaller than NA. Water absorbsion of RCA from Istanbul was 7,49 %, water absorbsion of RCA from Berlin was 4,3% and water absorbsion of NA was 2,65%. When percentage of fine RCA in concrete increased, density of concrete increased. Because fine RCA demanded more water in concrete. Using superplasticizer provided to decrease water consumption in concrete. Density of fresh concrete and density of hardened concrete were almost the same.

5.3 Chloride Content

Chloride content of RCA and concrete made with RCA is suitable for regulations in DIN EN 4226-100 except RCA from Istanbul size between 0-2 mm and 8-22 mm. Chloride content has to be smaller than 0,04 in M. % based on initial weight.

5.3.1 Chloride in RCA

Table 5.14 : Water soluble chloride (Cl^{-}) in RCA.

Sample Name	Concentration (mg/l)	Dilution	Chloride in M. % based on initial weight
RCA Berlin (2-8 mm)	13,951	1	0,014
RCA Berlin (8-16 mm)	0,938	20	0,019
RCA Istanbul (0-2 mm)	3,086	50	0,154
RCA Istanbul (2-8 mm)	13,951	1	0,014
RCA Istanbul (8-22 mm)	3,334	50	0,167

5.3.2 Chloride in concrete specimens

Table 5.15 : Water soluble chloride (Cl^{-}) in concrete made with RCA.

Sample Name	Concentration (mg/l)	Dilution	Chloride in M. % based on initial weight
Concrete made with 20% RCA Istanbul	10,834	1	0,011
Concrete made with 20% RCA Berlin	9,118	1	0,009
Concrete made with 50% RCA Istanbul	16,958	1	0,017
Concrete made with 50% RCA Berlin	15,846	1	0,016

5.4 Sulfate Content

Sulfate content of RCA and concrete made with RCA is suitable for regulations in DIN EN 4226-100. Sulfate content has to be smaller than 0,8 in M. % based on initial weight.

5.4.1 Sulfate in RCA

Table 5.16 : Water soluble sulfate (SO_4^{2-}) in RCA.

Sample Name	Concentration (mg/l)	Dilution	Sulfate in M. % based on initial weight
RCA Berlin (2-8 mm)	17,951	1	0,018
RCA Berlin (8-16 mm)	26,660	20	0,533
RCA Istanbul (0-2 mm)	15,429	50	0,771
RCA Istanbul (2-8 mm)	17,931	1	0,018
RCA Istanbul (8-22 mm)	12,332	50	0,617

5.4.2. Sulfate in concrete specimens

Table 5.17 : Water soluble sulfate (SO_4^{2-}) in concrete made with RCA.

Sample Name	Concentration (mg/l)	Dilution	Sulfate in M. % based on initial weight
Concrete with 20% RCA Istanbul	9,343	1	0,009
Concrete made with 20% RCA from Berlin	15,898	1	0,016
Concrete made with 50% RCA from Istanbul	29,477	1	0,029
Concrete made with 50% RCA from Berlin	17,931	1	0,018

Table 5.18 : Acid soluble sulfate (SO_3) in RCA.

Sample Name	Sulfate in M. % based on initial weight
RCA from Berlin (2-8 mm)	0,018
RCA from Berlin (8-16 mm)	0,533
RCA from Istanbul (0-2 mm)	0,771
RCA from Istanbul (2-8 mm)	0,018
RCA from Istanbul (8-22 mm)	0,617

5.5 Fog Chamber and Conrete Microstructure

Visual inspection of concrete samples made with RCA from Istanbul and RCA from Berlin was shown in Figure 5.6. In this figure, concrete sample on the left hand side was concrete made with RCA Berlin and on the right hand side was concrete made with RCA Istanbul. It was seen no visual visible evidence of ASR.

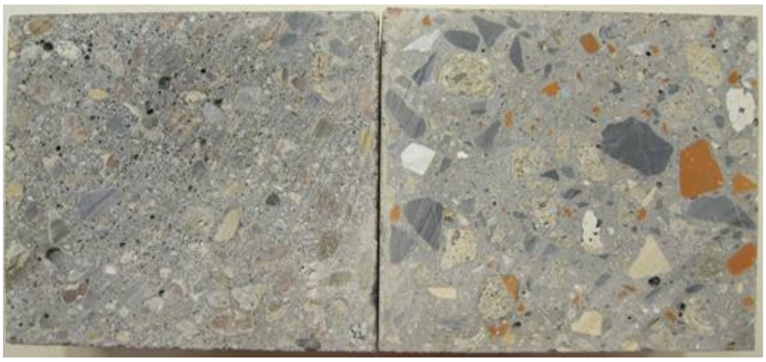


Figure 5.10: Concrete specimens made with RCA Istanbul and Berlin.

Microscopic analysis of concrete specimens was done to see if ASR reaction occured. After one month in the fog chamber (40 °C and 100 % relative humidity), none of concrete specimens were showed any sign of white alkali gels and damage. Concrete microstructure was shown in following figures: Concrete made with RCA Berlin at 5 mm length scale was shown in Figure 5.7, concrete made with RCA Berlin at 2 mm length scale was shown in Figure 5.8, Figure 5,9 and Figure 5,10. Concrete made with RCA Istanbul at 5 mm length scale was shown in Figure 5.11, concrete made with RCA Berlin at 2 mm length scale was shown in Figure 5.12, Figure 5,13 and Figure 5,14.

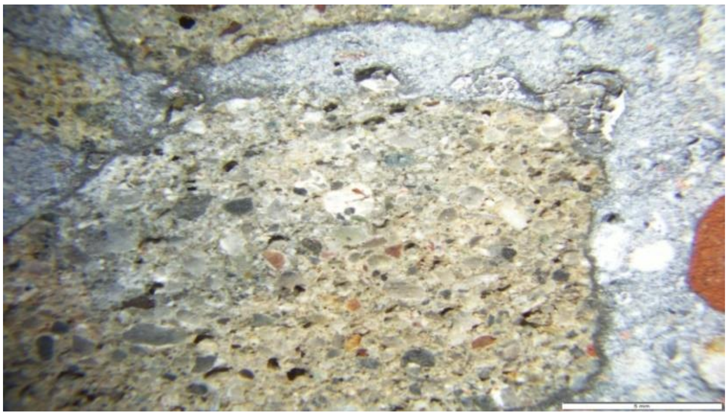


Figure 5.11 : Concrete made with RCA Istanbul at 5 mm length scale.

Figure 5.12 : Concrete made with RCA Istanbul at 2 mm length scale.

Figure 5.13 : Concrete made with RCA Istanbul at 2 mm length scale.

Figure 5.14 : Concrete made with RCA Istanbul at 2 mm length scale.

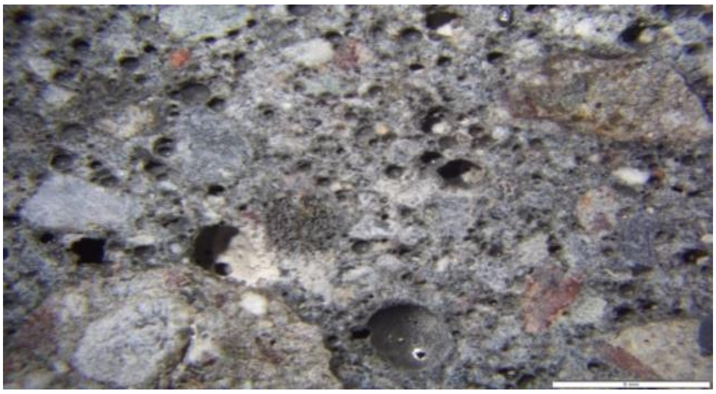


Figure 5.15 : Concrete made with RCA Berlin at 5 mm length scale.

Figure 5.16 : Concrete made with RCA Berlin at 2 mm length scale.

Figure 5.17 : Concrete made with RCA Berlin at 2 mm length scale.

Figure 5.18 : Concrete made with RCA Berlin at 2 mm length scale.

6. CONCLUSIONS AND RECOMMENDATIONS

Use of RCA from C&D waste in concrete is beneficial in terms of economic and environmental sustainability. To decrase C&D waste landfilling is easier than recycing however to find a landfill is a problem. Hence, recycling provides to conserve natural resources for next generations. Besides, NA crushing costs more than recycling of C&D waste and sell price of RCA is less than NA.

Concrete recycling is profitable in most cases. RCA already meet the requirements of lower value product applications such as road base and therefore it can be developed to have better structural, mechanical and chemical properties and higher quality material for structural use.

RCA can be used in concrete if they satisfy criterias and requirements in the norms.

Compressive strength of concrete is inversely proportional to the water/cement ratio. Concrete made with RCA required more water during the experiments. More water in concrete causes less compressive strength and density. In order to increase compressive strength of concrete, compressive strength of cement should be increased. Increasing dosage of cement and decreasing water quantity in concrete mixture are other solutions to increase compressive strength of concrete. In order to have less water consumption in concrete, fine aggregate should be chosen from NA instead of RCA and superplasticizer is important to control water consumption.

Concrete made with RCA has low compressive strength and density when the percent of RCA is increased in the concrete mixture.

Concrete made with RCA is applicable for structural use and non-aggressive exposure conditions. RCA should be analyzed for chemical contents and ASR should be investigated for long term use.

REFERENCES

[1] **Çevre ve Şehir Dergisi** (2013). Nisan 2013, Sayı 16. Ankara.

[2] **Karaca F. M.** (2012). İstanbul, Tuzla-Aydınlı İnşaat ve Yıkıntı Atıkları Geri Kazanım Tesisi İşletimi, *Atık Yönetimi Sempozyumu* date: 26.04.2012.

[3] **Fischer C. and Werge M.** (2009). EU as a Recycling Society Present Recycling Levels of Municipal Waste and Construction & Demolition Waste in the EU *ETC/SCP working paper 2/2009* date: April 2009.

[4] **Weisleder S. and Nasseri D.** (2006). Construction and Demolition Waste Management in Germany, *COWAM Intensive Workshop,* 25th September 2006, Hamburg.

[5] **Rühl M.** (1997). Water Absorption Capacity of Recycled Demolition Rubbish, *Darmstadt Concrete 97,* Ausgabe 12.

[6] **Lemmer C., Rühl M. and Nealen A Xiao J., Li J. and Zhang C.** (1998). Correction Of Consistency Of Concrete Made With Aggregate Derived From Concrete, *Darmstadt Concrete,* Annual Journal 13.

[7] **Huang W. L., Lin D. H., Chang N. B. and Lin K. S.** (2002). Recycling of Construction and Demolition Waste via a Mechanical Sorting Process, *Conservation and Recycling* 37 (2002) 23-37.

[8] **Khatib J.M.** (2005). Properties of Concrete Incorporating Fine Recycled Aggregate, *Cement and Concrete Research 35* (2005) 763– 769.

[9] **Xiao J., Li J. and Zhang C.** (2005). Mechanical Properties of Recycled Concrete Under Unaxial Loading, *Cement and Concrete Research* Volume 35, Issue 6, June 2005, Pages 1187–1194.

[10] **Falkner, H., Sun, Y., and Xiao J.** (2005). Seismic Performance of Frame Structures with Recycled Aggregate Concrete, *Engineering Structures* 28 (2006), 1-8.

[11] **Köken A., Köroğlu M. A., Yonar F.** (2008). Atik Betonlarin Beton Agregasi Olarak Kullanilabilirliği, *Selçuk Üniversitesi Teknik Bilimler Meslek Yüksekokulu Teknik Online Dergi,* ISSN 1302/6178, Cilt 7, Sayı:1-2008.

[12] **Tam V. W.Y.** (2008). Economic Comparison of Concrete Recycling: A Case Study Approach, *Conservation and Recycling* 52 (2008) 821–828.

[13] **Durmuş G., Can Ö. And Şimşek O. M.** (2009). Geri Dönüşüm Agregalardan Üretilen Farklı Sınıflardaki Betonun Mühendislik Özelliklerinin Belirlenmesi. *5. Uluslararası İleri Teknolojiler Sempozyumu,* Karabük Üniversitesi, Türkiye, 13-15 Mayıs 2009.

[14] **Achtemichuk S., Hubbard J., Sluce R. and Shehata M. H.** (2009). The Utilization of Recycled Concrete Aggregate to Produce Controlled

Low-Strength Materials without Using Portland Cement, *Cement & Concrete Composites* 31 (2009) 564–569.

[15] **Evangelista L. and Brito J.** (2009). Durability Performance of Concrete Made with Fine Recycled Concrete Aggregates, *Cement & Concrete Composites* 32 (2009) 9–14.

[16] **Yaprak H., Aruntas H. Y., Demir I., Şimşek O. and Durmuş O.** (2011). Effects of the Fine Recycled Concrete Aggregates on the Concrete Properties, *International Journal of the Physical Sciences* Vol. 6(10), pp. 2455-2461, 18 May 2011.

[17] **Lovato P. S., Possan E., Molin D. C. C. D., Masuero Â. B., Ribeiro J. L. D.** (2012). Modeling of Mechanical Properties and Durability of Recycled Aggregate Concretes, *Construction and Building Materials* 26 (2012) 437–447.

[18] **Thomas C., Setién J., Polanco J.A., Alaejos P., Juan M. S.** (2012). Durability of Recycled Aggregate Concrete, *Construction and Building Materials* 40 (2013) 1054–1065.

[19] **Manzi S., Mazzotti C. and Bignozzi M.C.** (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate, *Cement & Concrete Composites* 37 (2013) 312–318.

[20] **Demirel C. and Şimşek O.** (2014). C30 Sınıfı Atık Betonun Geridönüşüm Agregasi Olarak Beton Üretiminde Kullanilabilirliği, S.Ü. Müh. Bilim ve Tekn. Derg., c.2, s.2, 2014.

[21] **Köroğlu M. A. and Köken A.** (n.d.). Düşük Mukavemetli Atik Betonlarin Beton Agregasi Olarak Kullanilabilirliği.

[22] **Patil S. P., Ingle G. S. and Sathe P. D.** (n.d.). Recycled Coarse Aggregates.

[23] **Skovgaard M., Hedal N., Villanueva A., Andersen F. M. and Larsen H.** (2009). Municipal Waste Management and Greenhouse Gases, *ETC/RWM working paper 2008/1* date: 31.01.2008.

[24] **Guidance on the Interpretation of Key Provisions of Directive 2008/98/EC on Waste** (2012). European Commission Directorate General Environment.

[25] **European Waste Catalogue and Hazardous Waste List** (2002). *Environmental Protection Agency* date: 01.01.2002.

[26] **Bayraktar E.** (2013). 2014 Yılı Bütçe Sunuşu (TBMM Plan ve Bütçe Komisyonu), T.C. Çevre ve Şehircilik Bakanlığı, 20.11.2013.

[27] **Öztürk M.** (2005). İnşaat/Yikinti Atiklari Yönetimi, *Çevre ve Orman Bakanlığı,* Ankara.

[28] **Hafriyat Toprağı, İnşaat ve Yıkıntı Atıklarının Kontrolü Yönetmeliği** (2004). 18 Mart 2004 tarih ve 406 Sayılı Resmi Gazete.

[29] **Ulusal Geri Dönüşüm Strateji Belgesi ve Eylem Planı 2014-2017** (2014). *T.C. Bilim, Sanayi ve Teknoloji Bakanliği Sanayi Genel Müdürlüğü,* Ankara.

[30] **Gesetz über die Beseitigung von Abfällen Abfallbeseitigungsgesetz (AbfG)** (1972). Bundesgesetzblatt Teil I, Nr.49, p. 873, 10 Juni 1972.

[31] **Gesetz über die Vermeidung und Entsorgung von Abfällen (Abfallgesetzes - AbfG)** (1986). Bundesgesetzblatt, Jahrgang 1986, 27.08.1986.

[32] **Act for Promoting Closed Substance Cycle Waste Management and Ensuing Environmentally Compatible Waste Disposal (Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umnweltverträglichen Beseitigung von Abfällen)** (1994). Federal Law Gazette I, p. 2705, 27 September 1994.

[33] **DIN 4226-100: 2002-02** (2002). Gesteinskörnungen für Beton und Mörtel -Teil 100: Rezyklierte Gesteinskörnungen, *Deutsche Norm.*

[34] **DIN 1045-2** (2008). Tragwerke aus Beton, Stahlbeton und Spannbeton Teil 2: Beton, Festlegung, Eigenschaften, Herstellung und Konformität – Anwendungsregeln zu DIN EN 206-1, *Deutsche Norm,* Berlin.

[35] **DIN EN 206-1:2001-07** (2001). Beton - Teil 1: Festlegung, Eigenschaften, Herstellung und Konformität Deutsche Fassung EN 206-1:2000, *Deutsche Norm,* Berlin.

[36] **DIN EN 206-1/A1** (2004). Beton -Teil 1: Festlegung, Eigenschaften, Herstellung und Konformität; Deutsche Fassung EN 206-1:2000/A1:2004, *Deutsche Norm,* Berlin.

[37] **DIN EN 206-1/A2** (2005). Beton - Teil 1: Festlegung, Eigenschaften, Herstellung und Konformität; Deutsche Fassung EN 206-1:2000/A2:2005, *Deutsche Norm,* Berlin.

[38] **DIN EN 12620** (2013). Gesteinskörnungen für Beton; Deutsche Fassung EN 12620:2013, *Deutsche Norm,* Berlin date: July 2013.

[39] **German Committee for Reinforced Concrete (DAfStb) - Code: Concrete with Recycled Aggregates** (1998). DAfStb-Richtlinie , Beton mit rezykliertem Zuschlag“Deutscher Ausschuss für Stahlbeton (DAfStb), Deutsches Institut für Normung e.V. (Hrsg.), Beuth, Berlin.

[40] **Lippok J. and Häßler D.** (2000). Abbruchverfahren in Deutschland, *Beitraganlässlich der European Demolition Association Konferenz (EDA) Maastricht*, VerkehrsbauUnion (VBU), Baumaschinenhandelsgesellschaft mbh (DBH).

[41] **Weil M**. (2003). Ressourcenschonung und Umweltentlastung bei der Betonherstellung durch Nutzung von Bau- und Abbruchabfällen, Dissertation Weil Stand 3.02.04.

[42] **TS EN 12504-1** (2002). Beton - Yapida Beton Deneyleri - Bölüm 1: Karot Numuneler - Karot Alma, Muayene Ve Basinç Dayaniminin Tayini, *Türk Standardı,* Ankara.

[43] **TS EN 12390-3** (2003). Beton - Sertleşmiş Beton Deneyleri - Bölüm 3 : Deney Numunelerinde Basınç Dayanımının Tayini, *Türk Standardı*, Ankara.

[44] **DIN EN 933-1:2012-03** (2012). Prüfverfahren für geometrische Eigenschaften von Gesteinskörnungen - Teil 1: Bestimmung der

Korngrößenverteilung - Siebverfahren; Deutsche Fassung EN 933-1:2012, *Deutsche Norm,* Berlin.

[45] **DIN EN 933-2:1996-01** (1996). Prüfverfahren für geometrische Eigenschaften von Gesteinskörnungen - Teil 2: Bestimmung der Korngrößenverteilung; Analysensiebe, Nennmaße der Sieböffnungen; Deutsche Fassung EN 933-2:1995, *Deutsche Norm,* Berlin.

[46] **DIN EN 1097-6** (2013). Prüfverfahren für Mechanische und Physikalische Eigenschaften von Gesteinskörnungen —Teil 6: Bestimmung der Rohdichte und der Wasseraufnahme, *Deutsche Norm,* Berlin.

[47] **DIN EN 197-1** (2001). Zement -Teil 1: Zusammensetzung, Anforderungen und Konformitätskriterien von Normalzement, *Deutsche Norm,* Berlin.

[48] **DIN EN 13263-1:2009-07** (2009). Silikastaub für Beton - Teil 1: Definitionen, Anforderungen und Konformitätskriterien**;** Deutsche Fassung EN 13263-1:2005+A1:2009, *Deutsche Norm,* Berlin.

[49] **DIN EN 934-2:2012-08** (2012). Zusatzmittel für Beton, Mörtel und Einpressmörtel - Teil 2: Betonzusatzmittel - Definitionen, Anforderungen, Konformität, Kennzeichnung und Beschriftung; Deutsche Fassung EN 934-2:2009+A1:2012, *Deutsche Norm,* Berlin.

[50] **Betontechnische Daten Ausgabe 2014** (2014). HeidelbergCement AG, Entwicklung&Anweldung, Leimen.

[51] **DIN EN 12350-5: 2009-08** (2009). Prüfung von Frischbeton - Teil 5: Ausbreitmaß; Deutsche Fassung EN 12350-5:2009, *Deutsche Norm,* Berlin.

[52] **DIN EN 12390-3: 2009-07** (2009). Prüfung von Festbeton - Teil 3: Druckfestigkeit von Probekörpern; Deutsche Fassung EN 12390-3:2009, *Deutsche Norm,* Berlin.

[53] **DIN EN 1744-1:2013-03** (2013). Prüfverfahren für chemische Eigenschaften von Gesteinskörnungen - Teil 1: Chemische Analyse; Deutsche Fassung EN 1744-1:2009+A1:2012, *Deutsche Norm,* Berlin.

[54] **DIN EN 459-2:2010-12** (2010). Baukalk - Teil 2: Prüfverfahren; Deutsche Fassung EN 459-2:2010, *Deutsche Norm,* Berlin.

[55] **DIN EN 196-2:2013-10** (2013). Prüfverfahren für Zement - Teil 2: Chemische Analyse von Zement; Deutsche Fassung EN 196-2:2013, *Deutsche Norm,* Berlin.

[56] **Thomas M.D.A., Fournier B., Folliard K.J. and Resendez, Y.A.** (2011). Alkali-Silica Reactivity Field Identification Handbook, FHWA-HIF-12-022, December 2011.

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