Effect of Waste Crumb Rubber Tyre as a Partial Replacement of Fine Aggregates on Fresh and Mechanical Properties of Concrete

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ABSTRACT

There is a rising threat caused by the growing abundance of Waste Tyre Rubber (WTR). The non-putrescible nature, and long time to disintegrate, of Waste Tyre Rubber (WTR), is a global health risk. The top places to find this bedevilment is Europe and North America. The time to tackle this menace is long overdue. In a decade from now, the amount of waste tyres in the environment might verily outnumber the human populations.

In previous researches, WTR has been used as coarse aggregates, and combined replacement of coarse and fine aggregates in ratio about 1:3. This study applied it as fine aggregates in 0-40% replacement by weight at 10% intervals, five mixes in all, including control concrete. First-instance replacement, 10-CR was the best CRC mix. It had about 20% reduction in slump; 30% for strength by compression, tension, and flexure; split-tensile strength after degradation at 200°C, and no visible surface or internal cracks subsequently after degradation, at 28-days. When tested for Rate of Water Absorption, VPV was less than 10%, and it also achieved an excellent 4.63 Km/sec on ultrasonic pulse velocity reading. Overall, 10-CR had least reduction in workability, strength, and durability. Despite this reductions, 10-CR was within admissible bounds of structural expectations.

Keywords: Waste Tyre Rubber (WTR), waste tyres, Crumb Rubber Concrete (CRC), fresh state, hardened state, workability, strength, durability, flexural, tensile, cement, concrete, loads.

ÖZ

Artan Atık Lastik Kauçuğu (ALK) dünyamız için büyük bir tehdit oluşturmaktadır. Çünkü doğada yok olması çok uzun sürede gerçekleşmektedir ve bundan dolayı da küresel bir sorun olacak karşımıza çıkmaktadır. Atık lastiğin en fazla olduğu bölgeler ise Avrupa ve Kuzey Amerika'dır. Bu tehdidin üstesinden gelmenin zamanı çoktan gelmiştir ve on yıl sonra, çevredeki atık lastiklerin miktarı insan nüfusunu geçebilecek durumdadır.

Daha önceki araştırmalarda, ALK iri agrega olarak kullanılmış ve iri ve ince agregaların yaklaşık 1:3 oranında kombine olarak değiştirilmesi ile uygulanmıştır. Bu yüksek lisans tezi çalışmasında ince agregalar halinde ağırlıkça %0-40 oranında %10 aralıklarla, kontrol betonu dahil toplam beş karışım halinde uygulanmıştır. İlk aşamada değiştirme, karışımlar arasında 10-CR en iyi CRC karışımı olarak belirlenmiştir. Taze betonun çökmede değerlerinde yaklaşık %20 azalma oldmuştur; basınç, çekme ve eğilme mukavemeti ise %30 azalma göztermiştir. Öte yandan 200^{o}C sıcaklığa maruz kalan numunelerde 28 günde görünür yüzey veya iç çatlak görülmemiştir. Su Emme Oranı için numuneler test edildiğinde ise, GBO değerinin %10'dan az olduğu ve ayrıca ultrasonik darbe hızı (UDH) okumasında ise mükemmel bir değer olan 4.63 km/sn elde edilmiştir. Genel olarak, 10-CR karışımı işlenebilirlik, mukavemet ve dayanıklılıkta en az azalmaya sahip olmuştur.

Anahtar Kelimeler: Atık Lastik Kauçuk (ALK), atık lastikler, Kırıntılı Kauçuk Beton (KKB), taze hal, sertleşmiş hal, işlenebilirlik, mukavemet, dayanıklılık, eğilme, çekme, çimento, beton, yükler.

DEDICATION

To My Family

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°C	Degree celsius
cm^3	Cubic centimetre
in.	inches
Kg/m^3	Kilogram per cubic metre
mm	millimetre
um	micrometre
CDW	Construction Demolition Waste
CR	Crumb Rubber
CRC	Crumb Rubber Concrete
GHG	Greenhouse Gas
HPC	High Performance Concrete
ITZ	Interfacial Transition Zone
MPa	megapascals
MT	metric tons
NAC	Natural Aggregate Concrete
NaOH	Sodium Hydroxide
RA	Rubber Aggregates
RAC	Recycled Aggregate Concrete
TL	Turkish Lira
TDF	Tyre Derived Fuel
UPV	Ultrasonic Pulse Velocity
VPV	Volume of Permeable Voids
WTR	Waste Tyre Rubber

Chapter 1

INTRODUCTION

1.1 Background of the research

The time span during which concrete was first developed depends on one's understanding of the term "concrete". Materials of old were crude components that came about by crushing gypsum or limestone. Lime also means crushed limestone. Cements is combined to sand and water, to give mortar; a material used to stick stones to each other. A long time ago, these materials were developed, combined with other constituents and, finally, metamorphose into current concrete (Gromicko, Shepard, & CMI, 2022).

Today's concrete is made from Portland or different cements, different aggregates of stone and sand, and water. It is a composite material produced utilizing fine and coarse full scale grew close by a fluid (cement stick) that sets (fixes) after a sufficiently lengthy timetable (Gromicko, Shepard, & CMI, 2022).

Concrete is maybe the most dependably utilized game plan materials. Mehta PK et al. (2014) described it as a construction material of tremendous use. This has been maintained because of its strength, flexibility, and low maintenance necessities during the lifetime of structures. Also, there is economic and extended accessibility of its components, which makes it extremely challenging to replace in numerous infrastructure applications. Current worldwide concrete productions are fixed around

25 billion tons each year. Its utilization from one side of the world to the next, matching by weight, is double the combination of steel, wood, plastics, and aluminum (TR Construction Omaha, 2020). From bridges to enormous buildings, concrete is the most included material in infrastructure. According to the Pennsylvania Aggregates and Concrete Association (PACA), 70% of the world populace occupy a concrete structure for residential purposes (SPECIFY concrete, 2019).

This expansive use leaves the climate similarly susceptible to the tremendous effect that follows. Growing speculations accuse concrete of massive contributions to greenhouse gas (GHG) outflows (SPECIFY concrete, 2019). This is as destructive streams that hurts our ozone layer. Concrete production is liable for 8% of all crimes against the ozone layer. Academics everywhere, are mobilizing to enhance ways of reducing unsafe conveyance that reaches the ozone layer when concrete is produced. This will further develop the carbon sequestration of the product (Lehne & Preston, 2018).

There is a worldwide call to work on the natural friendliness of concrete. A great deal of research has singled out cement production and its utilization in concrete. Tremendous work has been finished over the last twenty (20) years to bargain weighty blows to this element of concrete. Most notable are; modifications of produced cement and development of cement replacement materials. A few research spells have investigated the enormous consumption of potable water in producing concrete, and the resultant effect on climatic conditions. Such researchers have evaluated concrete production with not exactly potable water, achieving some degree of success.

In this research, the focus is on aggregates. Among the many natural impacts of mining aggregates, is the converting of use of land, in existing functions from lacking or agricultural land use, to an unnecessary open in the earth (Environmental Impacts Of Mining Natural Aggregate, 2003). This significant reverberation is followed by loss of natural surroundings, commotion, breeze-with-sand, impacting come-abouts, disintegration, deposition of sediments, and alterations to the ambience of nature. The mining of stones can leave adverse ecological footprints on the earth. Political tensions seldom benefit this cause, and could worsen the ecological wreck around aggregate production in many instances. Regardless of every one of these, we cannot disdain the convenience of aggregates in concrete. Aggregates contribute to the blend and compactness of concrete. They can decrease the volume of cement paste, contribute hugely to the mechanics of concrete, and maintain the permanence of inflexible structures. In this way, we will investigate ecofriendly options with great accessibility for replacing natural aggregates in concrete.

1.2 Statement of the problem

Any kind of transportation today, should include some interaction with a vehicle, or whatever other hardware that looks comparably much. What is common pretty much all vehicles, is the utilization of tyres. This transcends even the uncommon ones for conveying labor and products. Man has walked through different developments as far back as the wooden tyres of 3500 B.C. to the advanced pneumatic tyre of the twentieth century. With truly increasing interest and technology, there is now an abundance of autos in circulation. According to Custom Engineered Wheels (CEW) Inc., almost 80 million cars were sold between 1990 and 2017. As at 2014, it is assessed that 1.8 billion vehicles man the street (Bellis, 2021). Tyres are intended to help the vehicle weight, assimilate shock; relay traction, vector, and slowing down forces to the street surface, maintain and direct change in movement (HANKOOK, 2022). Coupled with configuration conditions, maintenance, utilization, climatic and ecological conditions; tyres should be at last replaced (tires-easy.com, 2019). A six-year final proposal is often labeled to SUV, off-road and much bigger tyres. Lesser sizes are informed for use concerning four years. In the tyre importance transferred, there is all a worldwide concern growing that the world should figure out how to evacuate utilized tyres, as well as End-of-Life-Tyres (ELTs). In many pieces of Europe, such tyres are processed into Tyre Derived Fuel (TDF); a valuable substance took care of to cement furnaces, nuclear energy plants, mash and paper factories, steel factories, and modern boilers (WBCSD, 2021). This is as yet insufficient when compared to the numbers each extended time of ELTs that come into circulation. Despite the fact that TDF has been promoted in times past as great other option, recent research shows that more ideal choices, such as; imaginative materials for civil engineering projects, and replacements for restricted natural resources, is conceivable. This doesn't scatter the turning over of involved tyres and ELTs for Tyre Derived Fuel (TDF); rather, it emphasizes a consummate way to deal with the remaining ELTs that actually show up at landfills while some cannot be traced. Researchers have fixed thirty (30) as the percentage of ELTs that either go to landfills, or dissolve into many bits within the environment, in many pieces of Europe. Waste Tyre Rubber (WTR) is a consistently growing danger to natural supportability. The removal of tyres, either scrap or ELT occupies a lot of significant landfill space, presents fire and natural risks. What's more, it is highly non putrescible which causes decomposition to require almost 100 years, followed by soil harming, unsafe chemical delivering, and the preferences.

A method for saving the earth from this catastrophe, will be to involve this WTR as a source of inventive materials for civil engineering projects. This can be finished by replacing the generally drained natural resources that produce aggregates for concrete, with WTR, which infers crumb rubber. This is a most thorough approach, and enduring arrangement. Because of the humongous measure of concrete produced yearly, it is almost outside the realm of possibilities for the Waste Tyre Rubber (WTR) in circulation to beat the interest of clumps in concrete, whenever made into ecofriendly aggregates.

1.3 Research questions – hypotheses

Are Waste Tyre Rubber (WTR) quickly becoming a natural menace? Are these ecofriendly aggregates practical to produce concrete of decent properties? Has this been attempted previously, and at what replacement levels?

Hypotheses – Aggregates got from Waste Tyre Rubber (WTR) can replace natural aggregates in producing reasonable concrete. This is mainly by replacement of the fine aggregates in ratios within 10-20%.

1.4 Aim of the research

The focus here is to produce concrete with crumb rubber; that is practicable, ideal in weight, can uphold structural load, that is sturdy, can endure forceful conditions, and can withstand degradation or is enhanced at elevated temperatures. The research further hopes to free the climate of the non-putrescible Waste Tyre Rubber (WTR) lying richly in neighboring surroundings. A definitive is to encourage recycling of WTR over the long haul, and make reasonable concrete out of these stuffs. To do this, the material (Waste Tyre Rubber) will be processed into suitable sizes for fine aggregates (<5mm). The ends of this point are to produce Crumb Rubber Concrete (CRC) that can suffice for: External walls and sections, as well as structural heaping;

private hearths and oven places; assortment of concrete establishments, private parkways, roads, back streets, and stopping slows down.

1.5 Scope of the research

This involves the investigation of Crumb Rubber Concrete (CRC) made by 0-40% (at 10% spans) fine aggregate substituted by crumb rubber (2.36 - 0.075mm). To do this, blend for concrete will be intended to decide extent of control concrete (before replacement ratios) will be gotten with close consideration of the writing. There is need to concentrate on the concrete constituents, crushed rock fine aggregate(<5mm), including crumb rubber, and crushed rock coarse aggregates (6.3 - 20 mm); this will include preparation and curing of specimens, particularly 150 mm cube for all tests, and 100 x 100 x 500 mm prisms for flexural tests. On the whole, six specimens for each test; three for 7-day, and three for 28-day ages, except pace of water absorption, and permeability, that are tested at just mature age. In setting up these specimens for tough and mechanical tests, the fresh properties of concrete at the hour of pouring will be tested. Additionally, nondestructive measures will be carried out on the specimens. The properties examined in this research are recorded below.

(i) Particle Size Distribution

(ii) Specific gravity, and absorption (of fine and coarse aggregates, plus crumb rubber)

(iii) Moisture content of aggregates (plus crumb rubber)

(iv) Bulk Density (of coarse aggregates)

(v) Air content

(vi) Water-cement ratio

(vii) Workability

(viii) Compressive strength

(ix) Split-tensile strength

(x) Flexural strength

(xi) Exposures to elevated temperatures

(xii) Hardness

(xiii) Penetration resistance

(xiv) Structural quality and integrity

1.6 Objectives of the research

To achieve the points of the research, we will:

(i) Evaluate by method of analysis, the fresh properties of Crumb Rubber Concrete (CRC). The fresh properties to be ascertained are; slump, vebe time, air content, and unit weight.

(ii) Evaluate mechanical and durability properties of Crumb Rubber Concrete (CRC) concrete by method of analysis. The mechanical and durability properties that are examined include; compressive strength, split-tensile strength, and flexural strength; pace of absorption, permeability, and degradation at elevated temperatures.

(iii) Represent collected results accordingly with structured examination.

(iv) Improve existing, and foster new characteristics of Crumb Rubber Concrete (CRC)

(v) Update existing literature.

1.7 Justification of the research

In the field of materials engineering today, quick advances are being made to move unto feasible options across all wide. Green Concrete isn't anything about color. Agarwal and Garg (2018) defined it as a concept of imbuing natural wellbeing into each consideration for concrete production; from raw materials manufacture to blend plan, to structural plan, construction, and service life. Also, Green Concrete is economical, maintains a strategic distance from charges of waste removal, utilizes less energy, causes least damage to climate, and produces higher durability generally speaking. The academic community within the materials engineering field has continued huge contributions unstopped, to the supportability of concrete production, remembering that after water, concrete is the second in consumption. This has prompted massive replacement of constituents in concrete production. Lots of research have spilled out over the course of the years endeavoring to replace cement in segments, with substances like fly ash and silica fume. Still on this, when looking at reinforcing concrete; research has come out in loads on the chance of ecological filaments, such as, waste glass, vegetative fiber, waste plastics, and that's just the beginning. Accordingly, focus is going to aggregates. These balls of different sizes account for 60-70% of the mechanical strength determined in concrete. Natural stores of rocks are decimated globally, many years, to serve concrete with aggregate. The academic community rushes to the rescue in this once more. The common trend is to investigate bountiful waste dwellings around us that can be processed to comparable aggregate sizes, and applied in concrete production. As right on time back as 1994, Eldin and Senouci had concentrated on the potential outcomes of replacing mineral aggregates with crumb rubber; they discovered that rubberized concrete (RuC) showed better esthetics, workability, and a lighter weight. When considering durability, it performed not exactly conventional, on openness to freeze-thaw cycles. This was same on openness to compressive and tensile loads; yet with a ductile, plastic failure mode, in contrast to the common weak nature of conventional concrete. This implies that rubberized concrete can go through a bigger displacement before failure. Since the turn of the 21st century, researchers have stayed up with the growing concern over Waste Tyre Rubber (WTR), and they have contributed gigantically in proffering arrangements. According to SCOPUS, one of the biggest abstract and citation data set, that covers excess of 11,000 distributers, and upwards of 36,000 titles; a search in the Engineering and Materials Science subject areas for review and research articles labeled 'crumb rubber concrete' showed a top-ward contribution by researchers. In the beyond three years, researchers in the community are accelerating more enthusiastically at turning out arrangements around here. A gander at the last three (3) years, distributed research on concrete made with crumb rubber has increased by 14% in 2019 from 2018, 29% in 2020 from 2019, and 53% in 2021 from 2020. Beyond the academic community, there is growing interest globally. The United Nations' Sustainable Development Goals 12 & 15 - to ensure sustainable consumption and production patterns; and to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss; cater to recycling of waste tyres, and combatting land take-up by waste rubber tyres. According to the United States Ecological Protection Agency (EPA), 2-3 billion tyres currently stockpile in the United States, starting around 1998. It is assessed that year-on-year increases are close to 279 million. Ill-advised removal of tyres is known to achieve air, soil, and water quality issues. Hence, the need to embrace this research to ascertain possible crumb rubber concrete properties, and subsequently, proffer a protected removal for Waste Tyre Rubber (WTR).

In the primer writing search, four articles among many brought about this review.

Mhaya A.M. et al. (2021) focused on the machine-like features and impact resistance of adjusted concrete with Ground Blast Furnace Slag (GBFS) and Discarded Rubber Tyre Crumbs (DRTCs). In replacement of both clump categories, with DRTCs of suitable size in ratio of 5-30%, they discovered reductions in flexural, tensile, and compressive strength; these were however within industry permissible figures demonstrating their helpfulness as a bounce back concrete for natural waste.

Islam M. T. et al. (2021) concentrated on the mechanics, and durability portrayed with rubberized concrete (RuC). They replaced both parts of aggregates independently in bits of 10, and 30%. They okayed replacement ratios of coarse rubber aggregates stay up to a maximum of 10%; however, with fine rubber aggregates, 10% and 30% replacement demonstrated great outcomes. This implies that fine aggregate replacement manages the cost of more removal of Waste Tyre Rubber (WTR) nevertheless conveys burning properties.

Gregori A. et al. (2019) concentrated on aggregate replacement with rubber particles when testing compressive strengths of concrete. In a combine of writing review, displaying, and testing; he worked out a solution known as Strength Reduction Factor (SRF) that relates the concrete compressive strength with percentage of rubber, to its comparable without rubber. They maintained that fine rubber aggregates or combination of fine and coarse rubber aggregates in replacing natural aggregates will beat coarse rubber aggregates on each covetous concrete property. Going by the creators. fine aggregates replacement with rubber shouldn't exceed 10% in areas of core structural need.

Siddika A. et al. (2019) reflected on the features and uses of concrete involving waste tyre rubber. They reviewed rheological properties, and discovered ideal replacement level to be 12.5-20% when replacing natural fine aggregates. They maintained that 25% ought to not be exceeded on any count, past which there is no decent semblance of rubberized concrete with conventional concrete. Moreover, they called for research on rubberized concrete when exposed to fire.

Gaining from the writing, this research will produce crumb rubber concrete by natural fine aggregate replacement. The limit for effectiveness of rubber aggregate replacement has been fixed at 25%. This research will investigate up to 30%, and 40% crumb rubber substitution of natural fine aggregates. By pushing the boondocks in such manner, we intend to achieve a concrete that takes up much more Waste Tyre Rubber (WTR) than recently researched, despite everything maintains covetous properties. Likewise, Siddika A. et al. (2019) called out the lack of information on warm properties of rubberized concrete. This research will offer consideration in such manner.

1.8 Limitations of the research

In this research, the unfamiliar component studied is crumb rubber within sizes 2.36mm – 0.075mm. The manner of application is replacement by weight (RW); as preferred to replacement by volume (RV), addition by weight (AW), and addition by volume (AV). This method of replacement by weight will be applied to replace fine aggregates in the mix at 578.90 Kg/m^3 at 10% - 57.89 Kg/m^3, 20% - 115.78 Kg/m^3, 30% - 173.67 Kg/m^3, 40% - 231.56 Kg/m^3. This research does not involve rubber fibers; recycled steel fibers (RSFs), mesh, or any other piece of steel that can be obtained from Waste Tyre Rubber (WTR).

Chapter 2

LITERATURE REVIEW

2.1 Inception

A significant problematic source of wastes that occur within the United States is scrap tyres. Based on 2003 data, it is assessed that 290 million waste tyres every year, are produced in the USA. There is a residual figure of 265 million in stockpiles. A worrisome gathering of tyres gives propensity fire and wellbeing dangers. This because, such occurrence is cumbersome, hurtful, and occupy precious ecological room (U.S. EPA, 2014).

According to Xue et al. (2013), waste tyres in the United States rank similarly with its human populace (Xue & Shinozuka, 2013). Comparative figures are additionally existing in the European Union (EU) (Alsaif, Bernal, Guadagnimi, & Pilakoutas, 2019). The two places now hold more than 1 billion scrap tyres, with the EU now having 30% offer. The remainder of the world combined, has 200% more (Md. Islam, Islam, Siddika, & Md. Al Mamun, 2021).

2.2 Concrete

The most widely involved construction material globally, is concrete. It assumes a major part in infrastructure and confidential buildings construction. It has a seemingness of artificial rock. "concretus", meaning "to grow together" is a Latin term for concrete. A material of coarse grains (clumps or fillings), embeds in a tough grid with a viscous-like (cement or binder), that runs everywhere within the clumps, and holds them together forms a composite material known as concrete. In other words, various size of aggregates, combine with a toughened combination of cement and water, to form concrete. The features of concrete may depend on constituents used, and the amounts of constituents in the mix.

Implanted particles or sections of clumps, held together by this limiting medium, make up this composite material. An easiest meaning of concrete can be written as

concrete = filler + binder

With concrete, comes a few well-known benefits; like low maintenance, capacity to work with reinforcement, capacity to consume waste, energy efficiency, castability, and economy (Zongjin, 2011).

2.2.1 Constituent of concrete - water

The chemical reaction of water and cement brings about workability in concrete. Ratio of water weight to cement weight in a blend, is reduced to a factor, known as water/cement ratio. A lower factor brings about more grounding in concrete, and reduces permeability occasionally.

2.2.2 Constituent of concrete - cement

To produce concrete, we need cement, a binder described as hydraulic. This means, it hardens when combined with water. The solidification of cement paste (cement plus water) in the presence of air, and when submerged, is known as hydration. What remains main for cement include: (1) strength increasing with age, (2) helping rheological developments before set (Zongjin, 2011).

2.2.3 Constituent of concrete - aggregates

Gravel and sand, combined as aggregates, address the grain skeleton of the concrete. Fissures within this grid, ought to be leveled with binder paste depending on the mix desired (Zongjin, 2011). Aggregates significantly affect concrete when it's fresh, or hardened.

2.3 Crumb Rubber Concrete (CRC)

Different variety of Waste Tyre Rubber (WTR) has been utilized in concrete, from as far back as Topcu, I.B. et al. (1991), and Eldin and Senoucci (1992). All the more recently, the term Crumb Rubber Concrete (CRC) is coming to the front. It is a new-on-the-construction-scene material with a lot of commitment. It is created by replacing aggregates with rubber crumbs when blending concrete. It is harmless to the ecosystem with some structural expectation (Topcu & Avcular, 1997; Eldin & Senouci, 1994).

2.3.1 Rubber crumbs as concrete constituent

This material is gotten by first crushing end-of-life tyres (ELTs) into little particles with a comparative fineness to sand. These "rubber crumbs" can substitute a given portion of fine aggregates utilized in the blending process of concrete. Simultaneously, tyre rubber breathes new lease of economic usefulness, plus relief for the interest weighing on deposits of natural sands (Engineering and Tech, 2018). Typical sizes in the writing start from 10, to as low as 0.075 mm.

2.4 Fresh properties of concrete

A completely mixed concrete, in a fluid flow of matter, that has its plasticity intact, is known as fresh concrete. The plastic condition of fresh concrete gives a period to move, lay, consolidate, and caress the surface. The properties of fresh concrete affect speed of work, and decision making. In addition, they determine how to handle, and consolidate fresh concrete. They may likewise affect the features when hardened.

2.4.1 Workability (slump & vebe)

According to ASTM C125, workability is the property that determines the expected work needed to control freshly mixed concrete portion with the least tendency to segregate (ASTM, 2021). The expression "control" includes the workings of laying, consolidating, and finesse, when fresh. Anon explained the workable nature of concrete when fresh as amounts of mechanics, or energy that expects full compacted concrete exclusive of segregation. Total energy needed to start, and maintain concrete consistency explains the expected concrete to lay a mix; this relies on the different properties through various states of matter, of the cement paste, coupled with friction within, existing between aggregate particles, on a side; on the other hand, there is the outside wear-and-tear between the surface of forms and concrete, then again. Fresh concrete workability goes by two aspects: cohesiveness and consistency. Cohesiveness is the capacity of fresh concrete to keep every one of the fixings intact uniformly, while consistency explains the effectiveness of fresh concrete flow. Customarily, consistency – the ability of concrete to flow; can be measured though various ways, including but not limited to; test of slump-cone, the compacting factor, or a ball penetration, and compacting factor test. Cohesion is evaluated by the Vebe test, as a record of the capacity of concrete to hold water (this is entyrely opposite to bleeding), plus the stone-holding capacity (something that is opposites of separation) when considering concrete mixtures in the plastic state. The ability to flow, of concrete that's fresh can affect the work expected for its consolidation. Lesser work is required for compaction of concrete with simpler flows. The requirement needed for consolidation of a fluid-like self-compacting concrete can be totally dispensed with. Even though, such a concrete must suffice for cohesion to keep together its constituents, especially the stones, in an orderly dispersion throughout the timeframe of placement.

Workability deems necessary, when considering the type of building, and the techniques necessary for placement, consolidation, and finesse. Concrete that suffices for time and placement, in monstrous formworks without separation, would refuse to work when considering dainty structural members. Also, concrete that works well with high-frequency vibrators for consolidation, might prove tough-to-handle, if tamping by hand is used.

2.4.1.1 Crumb rubber effect on workability

In previous studies, rubber ash (powder) substituted fine aggregate. This was done by Zhuoming, C. et al. (2019), Aldahdooh, M.A.A. et al. (2016), Aly, A.M. et al. (2019), Ismail, M.K. et al. (2018), Farnoosh, J. et al. (2019), Girskas and Nagrockciene (2017), Ismail M.K. et al. (2017), Mohammed, B.S. et al. (2018), and Mendis A.S.M. et al. (2017); in mesh #20, <600 microns, 70% from size mesh 40, 600 – 1000 microns, 1 – 6 mm, 1 – 8 mm, 0.5 – 0.67 mm, 4.75 mm or less, one-fifths of 3 – 5 mm and two-fifths of 1 – 3 mm; and, 25% of 2 – 4 mm and 35% of 1 – 3 mm sizes respectively. Most of the authors maintained that workable nature of concrte decreased. Among the few reasons, is the surface roughness of crumb rubber, this inreases friction in the compound of concrete. Others like Zhuoming, C. et al. (2019), and Aldahdooh, M.A.A. et al. (2016); have bemoaned the presence of rubber dust and fluff that comes with crumb rubber. This is adverse to workability (Zhuoming, Lijuan, & Xiong, 2019; Aldahdooh, Bunnori, Johari, Jamrah, & Alnuaimi, 2016; Aly A. , El-Feky, Kohail, & Nasr, 2019; Ismail, Sherir, Siad, Hassan, & Lachemi, 2018; Jokar F. , Khorram, Karimi, & Hataf, 2019; Girskas & Nagrockienė, 2017).

Rubberized concrete that uses ash rubber and crumb rubber showed excellent workings when compared to normal concrete. This regard was so, up to 50% replacement, but not without the aid of admixtures (Senin, Shahidan, Abdullah, Guntor, & Leman, 2017). Crumb rubber reduced workability where superplasticizer was missing (Kumar & Lamba, 2017). Mandal et al. 2017 noticed workability to increase at 5% prior to reduction when substituting fine aggregates with crumb rubber in 0-20% at 5%

stretches (Mandal, Chakraborty, & Samanta, 2017). Larger part of the examinations has shown decreased workability on incorporation of crumb rubber (Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021). The vast majority of the examinations revealed that the workable nature reduced with a rise in CR amounts, this was made sense of by the reason that there is high hydrophobia of CR particles, they develop floating affinity prompting isolation (Yang, Chen, Guo, & Xuan, 2021; Hossain, Shahjalal, Islam, Tiznobaik, & Alam, 2019; AbdelAleem & Hassan, 2019; Onuaguluchi & Panesar, 2014). However, few examinations have revealed that incorporation of little amounts of crumb rubber (<20%), substituted for fine aggregates, can raise the workable level of concrete because of low water ingestion of crumb rubber (Khaloo, Dehestani, & P., 2008; Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Youssf, Mills, & Hassanli, 2016). It is worthy to take note of that different creators have announced crumb rubber to have allowable assimilation. The slump of CRC dropped (Alsaif, Koutas, Bernal, Guadagnini, & Pilakoutas, 2018) comparably, to natural aggregates concrete (NAC) case. This was additionally revealed by Alsaif et al. (2018). Crumb rubber rose and reduced the slump, due to unpleasantness that comes with its surface. The bigger particles showed higher internal friction; there is more energy requirement to overcome the hindrance of flow (Ramdani, Guetella, Benmalek, & Aguiar, 2019). Fine pollutions (rubber residue and cushion) likewise demand increased volume of water in order to obtain appropriate workable levels, without this, might hinder the flow of CRC (Alsaif, Koutas, Bernal, Guadagnini, & Pilakoutas, 2018; Chen, Li, & Xiong, 2019). However, some finders did detail a rise in slump because of crumb rubber inclusion. The rise in workable levels of CRC was ascribed to the reduced water assimilation of crumb rubber (Murugan & Natarajan, 2015; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

In previous studies, rubber ash (powder) replaced fine aggregate. This was done by Zhuoming, C. et al. (2019), Aldahdooh, M.A.A. et al. (2016), Aly, A.M. et al. (2019), Ismail, M.K. et al. (2018), Farnoosh, J. et al. (2019), Girskas and Nagrockciene (2017), Ismail M.K. et al. (2017), Mohammed, B.S. et al. (2018), and Mendis A.S.M. et al. (2017); in mesh #20, <600 microns, 70% from size mesh 40, 600 – 1000 microns, 1 – 6 mm, 1 – 8 mm, 0.5 – 0.67 mm, 4.75 mm or less, one-fifths of 3 – 5 mm and two-fifths of 1 – 3 mm; and, 25% of 2 – 4 mm and 35% of 1 – 3 mm sizes respectively. Most of the authors maintained that workable nature of concrte decreased. Among the few reasons, is the surface roughness of crumb rubber, this inreases friction in the compound of concrete. Others like Zhuoming, C. et al. (2019), and Aldahdooh, M.A.A. et al. (2016); have bemoaned the presence of rubber dust and fluff that comes with crumb rubber. This is adverse to workability (Zhuoming, Lijuan, & Xiong, 2019; Aldahdooh, Bunnori, Johari, Jamrah, & Alnuaimi, 2016; Aly A. , El-Feky, Kohail, & Nasr, 2019; Ismail, Sherir, Siad, Hassan, & Lachemi, 2018; Jokar F. , Khorram, Karimi, & Hataf, 2019; Girskas & Nagrockienė, 2017; Ismail, Hassan, & Hussein, 2017).

2.4.2 Air content of concrete

The air content is how much air contained within a concrete component, typically communicated as a percentage.

2.4.2.1 Crumb rubber effect on air content

Khatib and Bayomy (1999) figured out larger content of air in mixes of concrete containing rubber aggregates relative to control (Khatib & Bayomy, 1999). It is widely acclaimed that even without any air-entrainment by admixtures, significant air content can be collected by utilization of rubber aggregates. Creators have marked the zero polar nature of rubber aggregates as a reasonable justification of this; coupled with the low rubber aggregates density which culminates in lighter unit weight of rubber concrete (Kumar & Lamba, 2017; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Ling T.C. et al. tried Crumb Rubber Concrete (CRC) in making clearing blocks. He tested separated with two gathering partitions of crumb rubber; which were 1-5 mm, and 1-3 mm; the two of them demonstrated to increase the air content, and reduce unit weight (Ling & Hasanan, 2009). The two of them showed around 10% reductions in unit weight for 25% crumb rubber replacement with respect to control. According to Mutar et al. (2018), the hydrophobic crumb rubber idea causes it to repulse water, and hence attract air. Basically, crumb rubber introduces bubbles into the concrete (MUTAR, HUSSEIN, & MALIK, 2018).

Mohammed et al. (2017) went ahead to label crumb rubber as an air entraining specialist, and further added that it has capacity to further develop freeze-thaw resistance (Mohammed, Adamu, & Shafiq, 2017). In some instance, the density of crumb rubber compared to sand has been essentially as low as 192%. Increased air entraining capacity of crumb rubber, combined with its light density has trickled down its unit weight (Richardson, Coventry, Edmondson, & Dias, 2016). In this light, Uygunoğlu and Topçu (2010), Adamu M. et al. (2017); recorded 26% increases on air content with 2% negligible misfortune on fresh density (Uygunoğlu & Topçu, 2010; Adamu, Mohammed, & Shafiq, 2017), when substituting fine aggregates by 1.5% weight with crumb rubber.

2.4.3 Unit weight of concrete

The fraction of concrete mass to a unit of its volume, the density, is an expression of its unit weight. Typically, ordinary unit weight of concrete weighs around 2136 Kg/m^3 in the evaporate conditions and could reach to 2400 Kg/m^3 when wetted together.

2.4.3.1 Crumb rubber effect on unit weight

Crumb rubber when applied to replace fine aggregates, reduced unit weight in all instances. Sukontasukkul P. et al. (2013) discovered same results with replacement ratios of 0, 50, 75, and 100% in sizes below 600 microns. Batayneh M. K. et al. (2013) discovered same results with replacement ratios of 0, 20, 40, 60, 80, and 100% in sizes 0.15 – 4.75 mm. Guneyisi E. et al. (2004) discovered same results with replacement ratios of 0, 2.5, 5, 10, 15, 25, and 50% in sizes 12.5 mm and below. Naoman A.T. et al. (2016) discovered same results with replacement ratios of 0, 5, 10, and 15% in sizes 1.18 – 2.36 mm. Pastor J.M. et al. (2014) discovered same results with replacement ratios of 0, 5, 10, 15, and 20% in sizes 0.6 – 2.36 mm. Thakur A. et al. (2020) discovered same results with replacement ratios of 0, 15, 25, 50, and 100% in sizes 0.075 – 4.75 mm. (Sukontasukkula, Jamnam, Rodsin, & Banthia, 2013; Güneyisi, Gesoğlu, & Özturan, 2004; Noamana, Bakar, & Md. Akil, 2016; Thakur, Senthil, Sharma, & Singh, 2020; Pastor, García, Quintanaa, & Peña, 2014).

Kumar et al. (2017) discovered that unit weight decreased by 6-9% on crumb rubber substitution of fine aggregates at varying proportions (Kumar & Lamba, 2017). The density of CRC is expected to fall below typical concrete because of the lower density of rubber, Prior investigations support this for cases of replacement by volume, or weight. It has been confirmed in the writing that crumb rubber conversely connects with concrete density. Ismail and Hassan (2017) focused on concrete density, and how crumb rubber impacted it; and found reductions as the amount of crumb rubber raised. Density of rubber which is low brought about lesser density of CRC, in addition, the associated ensnared air existing side-by-side with mortar of cement, and rubber particles, which rose proportionately with the crumb rubber amount (Ismail & Hassan, 2017; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Ling T.C. et al. (2009) tried Crumb Rubber Concrete (CRC) in making clearing blocks. He tested separated with two gathering crumb rubber sizes; 1-5 mm, and 1-3 mm; the two of them demonstrated to increase the air content, and reduce unit weight (Ling & Hasanan, 2009). The two of them showed around 10% reductions in unit weight for 25% crumb rubber replacement with respect to control. According to Mutar et al. (2018), the hydrophobic state of crumb rubber causes water repulsion, and hence attract air. Basically, crumb rubber introduces bubbles into the concrete (MUTAR, HUSSEIN, & MALIK, 2018; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

2.5 Mechanical and durable properties of concrete

As hydration carries on during the cure time, concrete metamorphoses from liquid to plastic state, lastly to strong hardened state. In this final, external burdens can descend upon concrete as a proper structural material (Zongjin, 2011). A few significant properties of hardened concrete include compression, split-strain, flexure, degradability because of intensity, permeability, and water ingestion.

2.5.1 Compressive strength

Compression testing estimating hardened concrete strength, is known as its compressive strength. Otherwise put as the proportion of concrete capacity to oppose loads which tend to compress it. It can be estimated by attempting to flatten laterally concrete specimens that are cylindrical, with the aid of a compression testing machine (Jamal, 2017).

2.5.1.1 Crumb rubber effect on compressive strength

Plenty findings have declared that compressive strength reduced as CR content rises within the mix. Authors like Abendeh R. et al. (2016), Batayneh M.K. et al. (2008), Guneyisi E. (2004), Choudhary S. et al. (2010), Noaman, A.T. et al. (2016), and Hesami S. et al. (2016) recorded compressive strength to reduce similarly, when replacing fine aggregates with size ranging from 0.6 – 4.75 mm commonly in replacement ratios of 0-50% at 5-10 intervals (Abendeh, Ahmad, & Hunaitib, 2016; Batayneh, Marie, & Asi, 2008; Güneyisi, Gesoğlu, & Özturan, 2004; Choudhary, Chaudhary, Jain, & Gupta, 2020; Noamana, Bakar, & Md. Akil, 2016; Hesami, Hikouei, & Ali Emadi, 2016).

In many cases, CR amount correspondingly crashed compressive strength. Salehuddin et al. (2015) with three parts (2.5, 5.0, and 7.5%) of CR substituting natural aggregates that are fine, assessed concrete compressive strength. The w/c ratios were set at 0.5, and 2 to 4 mm for crumb rubber size. It is on record that compressive strength encountered gradual reductions as the amount of crumb rubber adds. Fall of density occurred due to sand giving way to light-dense crumb rubber. This was judged as responsible for compressive strength performance (Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015). Also, it was noised abroad that there was weaker ITZ existing in the joining point of cement mortar and rubber particles, compared to where cement mortar and natural aggregates meet. Adding to this, difference in the unbending nature existing side-by-side the coming together of cement with the rubber particles, produce elevated-stress concentrations at points of interfacial zones prompting crack development in this familiar terrain, this forms the easy way out to the heap twisting (Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Bisht and Ramana (2019) explored different avenues regarding crumb rubber of size 600 microns replacing fine aggregates by percentage of mass 4, 4.5, 5, and 5.5%; with 0.4 as w-c/w-b ratio, and normal concrete of 34.3 MPa. He tracked down reductions of 3.8, 11.7,15.2, and 17.8% respectively (Bisht & Ramana, 2019).

Different avenues regarding crumb rubber of size 2-4mm replacing fine aggregates by weight in percentages of 2.5, 5, and 7.5%; with ratio of 0.5 for w-c/w-b, and control blend of 30.68 MPa; were explored by Salehuddin et al. (2015). He tracked down reductions of 6.1, 15.9, and 29.9% respectively (Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015).

Thomas et al. (2014) explored different avenues regarding crumb rubber size of gatherings; one-quarter of 2-4mm, seven-twentieth of 0.8-2mm, and two-fifths part of rubber powder; replacing fine aggregates by weight in percentages of 2.5 - 20% at 2.5 intervals, of fine aggregates; with 0.4, 0.45, and 0.5, as ratio of w-c/w-b, and control blend of 42.5, 39, and 36 accordingly. He tracked down the following reductions: for w/b ratio of 0.4; 3.5, 11.8, 12.9, 21.2, 29.4, 41.2, 45.2, and 52.9% respectively going by the previously mentioned percentages replacements. Likewise for paste ratio of 0.45, the reductions were; 2.6, 15.4, 21.8, 29.5, 35.9, 44.9, 44.9, and 48.7% respectively. In a similar respect, ratio of paste of 0.5, the reductions were; 7.7, 15.9, 19.7, 34.2, 41.6, 49.9, 52.1, and 53.4% respectively (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014).

Dehdezi et al. (2015) explored different avenues regarding crumb rubber of size 2-4 mm replacing fine aggregates by weight in percentages of 20 and half; with 0.54 as w-c/w-b ratio, and control blend with 39 MPa strength. He tracked down reductions of 22, and 30% respectively (Dehdezi, Erdem, & Blankson, 2015).

Jokar et al. (2019) explored different avenues regarding crumb rubber of size 1-6 mm replacing coarse aggregates by weight in percentages of 0, 5, 10, and 15%; with w-c/w-b ratio of 0.48, and control blend of 35 MPa. He tracked down reductions of 22.9, 40, and 51.4% respectively (Jokar F. , Khorram, Karimi, & Hataf, 2019).

Zaleska et al. (2019) explored different avenues regarding crumb rubber of size 5 mm replacing coarse aggregates by weight in 10, 20, and 30% percent; with 0.5 w-c/w-b ratio, coupled with control blend of 64.5 MPa. He found reductions 55.8, 80.9, and 91.9% respectively (Zaleska, Pavlikova, Citek, & Pavlik, 2019).

Overall, the writers are in one accord, crediting the interface existing side-by-side with crumb rubber and cement mortar as essential to reduction of compressive strength. Their clarion call is to treat crumb rubber to work on the interfacial bond in CRC.

2.5.2 Split-tensile strength

Concrete is certainly not a tensile material; hence we apply the indirect tensile strategy to decide its qualities. The proportion of the most extreme stress on the strain face of an unreinforced concrete member, is known as parting tensile strength. This strength isn't independent of factors such as water to cement ratios, slump, fixing proportioning, and others.

2.5.2.1 Influence of crumb rubber on split-tensile strength

In the writing, parting tensile strength reduced from 5.7-66.67% with 5-30% replacement of aggregates by crumb rubber (Thomas & Gupta, 2015; Turatsinze, Bonnet, & Granju, 2007). According to Kumar K. et al. (2017), split-tensile strength decreased from 12-28% for replacement parts of fine aggregates going from 2.5-7.5% accordingly (Kumar & Ankit, 2017; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Split-tensile strength reduced and increased alike, when crumb rubber replaced fine aggregate in concrete. Guneyisi E. et al. (2004) observed reduced split-tensile strength when he used according to replacement levels of 0, 2.5, 5, 10, 15, 25, 50%, and with sizes of 3 mm. However, when Hossain F.M.Z. et al. (2019) replaced crumb rubber in ratios of 0, 10, and 30%, with size less than 4.75 mm, he found increment in split-tensile strength (Güneyisi, Gesoğlu, & Özturan, 2004; Hossain, Md.Shahjalal, Islam, Tiznobaik, & Alam, 2019).

2.5.3 Flexural strength

Concrete can withstand bending forces applied perpendicular to its longitudinal axis to a certain degree, this is known as flexural strength. An unreinforced concrete shaft or piece oppose failure in bending in a proportion known as flexural strength (NRMCA, 2000). Modulus of Rupture (MOR) is same as flexural strength (Zongjin, 2011).

2.5.3.1 Crumb rubber effect on flexural strength

Similarly, flexural strength fell as reported by Batayneh M. K. et al. (2013), Hesami S. et al. (2016), Hossain F.M.Z. et al. (2019), and Thomas B.S. et al. (2014); typical sizes ranged from 0.15 – 4.75 mm in replacement ratios of mainly 0-20% at 2-10 intervals (Batayneh, Marie, & Asi, 2008; Hesami, Hikouei, & Ali Emadi, 2016; Hossain, Md.Shahjalal, Islam, Tiznobaik, & Alam, 2019; Thomas B. S., Gupta, Kalla, & Cseteneyi, 2014).

Thomas et al. (2014) explored different avenues regarding crumb rubber of gatherings; one-quarter of 2-4mm, seven-twentieth of 0.8-2 mm, and two-fifths part of rubber powder, replacing fine aggregates by weight in percentages of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%; with 0.4, 0.45, and 0.5 as w-c/w-b ratio, and control blend of 5.32, 5.28, and 5.12 respectively. /For the blend of 0.4 w/b ratio, he tracked down reductions of 2.3, 5.8, 9.8, 14.3, 15.8, 21.8, 24.1, and 24.8% going by the previously mentioned percentage replacements. In a similar request, for 0.45 w/b blend, he tracked down changes of +0.8, - 4.2, - 6.4, - 11.9, - 14.4, - 19.7, - 23.5, and - 24.2% respectively. For the blend of 0.5 w/b ratio, he tracked down reductions of 0.8, 3.1, 8.2, 14.8, 18.0, 18.8, 21.9, and 26.6% respectively (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Thomas and Gupta (2016) explored different avenues regarding crumb rubber gatherings. A tripartite combination of 2-4mm, 0.8-2 mm, and rubber powder; in sharing portions of one-quarter, seven-twentieth, and two-fifths respectively; replaced fine aggregates by weight in percentages of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%. W-c/w-b ratio was 0.3, and control blend of 7.2 MPa. For the blend of 0.3 w/b ratio, he tracked down changes of +1.4, - 4.2, - 4.2, - 8.3, - 15.3, - 17.5, - 17.5, and 23.6% going by the previously mentioned percentage replacements (Thomas & Chandra, 2016).

2.5.4 Heat degradation

Concrete is tough in fire, nonetheless, it can suffer mechanically, physically, and chemically at severe temperatures (Ndoukouo, Nabissie, & Woafo, 2011; Sakr & El-Hakim, 2005). There are main reasons that can determine the concrete performance when encountering elevated temperatures. Concrete is susceptible to spall, crack, loose density, give up moisture, dehydrate, and encounter loss of strength. Other deciders regarding concrete behavior on fire exposures include; fire intensity, transverse reinforcements, placing, type of aggregates, and reinforcement (Ghadzali, et al., 2018).

2.5.4.1 Crumb rubber influence on elevated temperatures

Tayebi et al. (2013) observed that the structure strength fell after high-temperatures heating because of quick development of the inner pore structure, this came about due to the inability of light aggregates to withstand raised temperatures. More research is currently finished to work on this respect (Al-Tayeb, Bakar, Ismail, & Akil, 2013). According to Bu et al. (2021), studies on the high-temperatures properties of rubberized concrete is as yet restricted. Specific changes in rubber aggregates after high temperatures should be noticed, and speculation about solid decline of specimen strength properties have not been validated by sufficient evidence (Bu, et al., 2022; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

2.5.5 Permeability

American Concrete Institute (ACI) defines permeability of concrete as its capacity to allow fluid or gases to go through (ACI). The control of the pace of flow of fluids into a permeable mass, is a property known as permeability. Largely, it depends on pore size, and pore connectivity; and how clear the path is for the pervading liquid. Pores of sizes 0.12-0.16 microns are generally essential to permeability. Chief reasons that rule concrete permeability are ratios of water-cement, compaction of concrete, concrete curing, and concrete period. Others include cement properties, aggregates, admixture utilization, and blending water loss (THE CONSTRUCTOR - Building Ideas, 2021).

2.5.5.1 Consequence of crumb rubber on permeability

Concrete durability relies on its permeability (Gupta, Chaudhary, & Sharma, 2016). It was expressed that CRC water permeability rose with rising amounts of crumb rubber. The rise in CRC permeability stems from modified porosity, and minor cracks that occur in the bonding zone between paste of cement, and crumb rubber. Binder (cement) pastes plus crumb rubber aggregates, experiences weak interfacial connection which increased concrete water permeability (Munoz-Sanchez, Arevalo-Caballero, & Pacheco-Menor, 2017) as Munoz-Sanchez et al. (2017) states. Ganjian et al. (2009) judged water penetration depth to rise as crumb rubber sizes went higher (Ganjian, Khorami, & Maghsoudi, 2009). Thomas et al. (2016) judged water penetration depth to rise in 20%-Crumb Rubber Concrete (CRC) with increment in the water-binder ratios (Thomas, et al., 2016). Su et al. (2015) additionally substituted crumb rubber with one-fifths of fine natural aggregates in 3-, 0.5-, and 0.3-mm sizes; he discovered maximal profundity for CRC concerning water penetration involving crumb rubber of sizes 3 mm or more (Su, Yang, Ling, Ghataora, & Dirar, 2015). Enormous-measured crumb rubber particles, or huge degree can prompt ill-advised dispersion of aggregates in concrete, which will further permeability in concrete (Su, Yang, Ling, Ghataora, & Dirar, 2015). In this manner, they cemented that CR particles of smaller sizes benefit impermeability cause in CRC. Bisht and Ramana (Bisht & Ramana, 2017) revealed that profundity of permeability rises when concrete with higher amounts of crumb rubber is tested. This is due to the voids of air captured when blending crumb rubber in concrete. The attribute of water-cement ratios, on CRC water penetration depths was explored by Thomas et al. (2014), and Gupta et al. (2016). Increased profundity of water penetration occurred as water-cement ratio increased. It was demonstrated that low-permeable concrete can be achieved given replacement levels do not exceed 15% (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014). Crack width formation by the rubber particles is prompted by the low-power connection that is shared between cement paste and crumb rubber (Gupta, Chaudhary, & Sharma, 2016). Oxygen, moisture, and other media that can disintegrate concrete take advantage of these cracks ruthlessly. Huge-estimated crumb rubber particles are not helpful, and will very much end in deeper, heavier, and larger cracks. Further, these cracks might interconnect on the off chance that an excessive amount of crumb rubber is utilized. Consequently, the size and evaluating of crumb rubber ought to be controlled to keep away from durability failure of Crumb Rubber Concrete (CRC) (Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

When Thomas et al. (2014) explored different avenues regarding crumb rubber (<4 mm), replacing fine aggregates by weight in 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%; for three water-binder ratios, 0.41, 0.45, and 0.5; they observed that increments were basically as high as 310, 275, and 163% for the water-binder ratios respectively (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014).

Bisht and Ramana (2017) explored different avenues regarding crumb rubber (of 0.6 mm), replacing fine aggregates by weight in 4, 4.5, 5, and 5.5%; for water-binder ratios of 0.4; they tracked down increments up to 35% with respect to control concrete (Bisht & Ramana, 2017).

Thomas and Gupta (2016) explored different avenues regarding crumb rubber of three packet of sizes; 2-4 mm, 0.8-2 mm, and rubber powder. He used these in ratio 0.25 : 0.35 : 0.4 respectively, replacing fine aggregates by weight in 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%; for water-binder ratios, 0.3; they found a stunning 225% increments with control concrete measuring 4 mm, 20%-CRC that recorded 13 mm penetration depth (Thomas & Chandra, 2016).

Bisht and Ramana (2017) tried replacing natural fine aggregates with crumb rubber in portions of 0, 4, 4.5, 5, and 5.5%; he found penetration by water depths to increase steadily with 30 mm for control, to about 40 mm for 5.5%-CR. This they accrued to continuous microcracking, owing to fine aggregates substitution by crumb rubber (Bisht & Ramana, 2017).

2.5.6 Rate of water absorption

Concrete water-snugness can be referred to as Rate of Water Absorption. This is the most inside and out test that checks concrete's capacity to withstand water entrance (Schutter & Audenaert, 2004). Structural application of concrete can include numerous hydraulic functions that request concrete structures to be to some extent, or completely lowered in water. It likewise fills in as a pointer to the (reachable) pore volume of the concrete (SMART CONCRETE, 2014).

2.5.6.1 Crumb rubber effect on rate of water absorption

The durability of concrete is highly impacted by water absorption. All the popular concrete chemical reactions are fostered by moisture. This is mainly how durability bows to the effects of water absorption in CRC. A few authors examined the effects of crumb rubber on CRC sorptivity. Plenty of the published outcomes have realized that higher crumb rubber amount increased CRC water absorption (Aliabdo, AEM, & MM, 2015; Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Pham, et al., 2019). Then again, a few researchers have detailed a contrary pattern i.e., higher amount of crumb rubber reduced water absorption, yet at resulting higher levels, there was a rise in the water absorption. Comparative perceptions were accounted for in different examinations (Bisht & Ramana, 2017; Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Mohammed & Azmi, 2011). Hence, the sorptivity of concrete rides along with the amount of crumb rubber, it is useful to limit to a cutoff, the amount of crumb rubber when regarding concrete durability. Ganjian et al. (2009) substituted coarse aggregates by up to 10% chipped rubber. They revealed that as crumb rubber amount increased, water absorption rose. Oppositely, ground rubber in concrete, substituting cement, decreased water absorption. Including oven-drying in procedure has shown altogether different outcomes on absorption percentages. The effect of this step is much pronounced (Ganjian, Khorami, & Maghsoudi, 2009). Discoveries from Bravo and De Brito (2012) likewise back this, their exploratory outcomes showed further water absorption as the amount of crumb rubber was raised (Bravo & De Brito, 2012). Gupta et al. (2014) finalized that water absorption relied on crumb rubber size and quantity, combined with the w/b ratio of the mix. A few examinations detailed decidedly on water absorption effect because of crumb rubber. Oikonomou and Mavridou (2009) announced that CRC placed in hydraulic vacuum retained minimal water within the gap of 7-25% having CR content as much as 15% (Oikonomou & Mavridou, 2009). Yilmaz and Degirmenci (2009) detailed reduced water absorption with larger size crumb rubber aggregates (Yilmaz & Degirmenci, 2009). Segre et al. (2004) proved that 10% CRC was a bit less than control concrete mixture in water absorption (Segre, Joekes, Galves, & Rodrigues, 2004). Wang et al. (2019) found that foamed concrete and under 3% crumb rubber displayed great waterproofing property. Some researchers aggreed that to a certain limit, water absorption reduced, before stepping onwards (Wang, Gao, Tian, & Dai, 2019; thomas & Gupta, 2015). Incorporating differing sizes of crumb rubber will further develop the aggregates degree (Si, Guo, & Dai, 2017) so that microstructure of heavier density happens, this will in turn promote favorable sorptivity, as Si et al. (2017) diagnosed. Bisht and Ramana (2017) explored different avenues regarding crumb rubber of size 600 microns replacing fine aggregates by weight in 4, 4.5, 5, and 5.5% of FA, and with w/c-w/b ratio as 0.4. He recorded a raise by 12.6, 26.2, 41.9, and 68.1%, accordingly (Bisht & Ramana, 2017).

Salehuddin et al. (2015) explored various replacement portions of 2.5, 5, and 7.5% crumb rubber substituting fine aggregates by weight, with sizes of 2-4 mm ad 0.5 as ratio for w-c/w-b. He tracked down increases of 42, 91, and 548% respectively

(Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Girskas and Nagrockiene (2017) explored different avenues regarding fine aggregates substitution by crumb rubber of size 0.1 - 3 mm by weight in percentages of 5, 10, and 20% of FA, and with w-c/w-b ratio of 0.35. He tracked down 4.95% increase difference for 20%-CR, compared to control that had 3.49% (Girskas & Nagrockiene, 2017).

Thomas et al. (2014) explored different avenues regarding crumb rubber size of three (3) gatherings, 25% of 2-4mm, 35% of 0.8-2mm, and 40% rubber powder; he replaced fine aggregates by weight in percentages of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20% with w-c/w-b ratio of 0.4, 0.45, and 0.5. He tracked down water absorption for the three water-binder ratios to be 0.25, 0.3, and 0.35% for control concrete respectively; and for 20%-CR, they were 0.5, 0.7, and 0.65% respectively (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014).

Thomas et al. (2015) explored different avenues regarding crumb rubber size of three (3) gatherings, 25% of 2-4mm, 35% of 0.8-2mm, and 40% rubber powder; replacing fine aggregates by weight in percentages of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%, and with 0.3 as w-c/w-b ratio. He found decrease for crumb rubber content up to 7.5%, past this, he recorded a converse trend (Thomas & Gupta, 2015).

Bisht and Ramana (2017) tried replacing natural fine aggregates with crumb rubber in portions of 0, 4, 4.5, 5, and 5.5%; he found absorption rates of 1.91, 2.15, 2.41, 2.71, and 3.21% respectively. This they accrued to the presence of voids that appear on replacement of fine aggregates with crumb rubber (Bisht & Ramana, 2017).

2.6 Non-destructive (pulse velocity) properties of concrete

A significant test that can give data on the similitude and constancy of crumb rubber concrete (CRC), and its blanks and rifts; is known as Ultrasonic Pulse Velocity (UPV). It can provide information on appearance of cracks, cavities, and voids within the concrete solid, on the concrete quality. The nature of concrete i.e., structural uprightness as an untouched evaluation by sensing of the ultrasonic wave, as it travels across the concrete specimen, can be decided by the Ultrasonic Pulse Velocity (UPV). A higher velocity indicates a more grounded nature of concrete.

2.6.1 Crumb rubber effect on concrete pulse velocity

Size 100 mm concrete cube was tested by this unharming method. There has been previous research to successfully assess concrete strength, by the UPV test. This test can be involved before testing compression by crushing, for similar examples. In general, Crumb Rubber Concrete (CRC) has lower UPV values than control concrete (Hesami, Salehi Hikouei, & Emadi, 2016; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021).

Girskas and Nagrockiene (2017) utilized crumb rubber shared into sizes of 2/4 and 4/6 mm substituting for natural fine aggregates in 5, 10, and 20% share according to volume. It was compiled that concrete UPV decreased as a result of rubber particles. They however kept up that those examples containing coarser rubber particles showed preferable UPV over those containing fine rubber particles. It was subsequently closed that sizes of crumb rubber, and content, dazzle on UPV values (Girskas & Nagrockiene, 2017).

Hesami et al. (2016) substituted crumb rubber of fine aggregates, going by 0, 5, 10, and 15%, with sizes of 0.15 to 4.75 mm. He found that UPV decreased as replacement ratio increased (Hesami, Salehi, & Emadi, 2016).

Essentially, Girskas and Nagrockiene (2017) tried crumb rubber as fine aggregate to substitute by weight in amounts of 0, 5, 10, and 20%, with sizes of 2/4 and 4/6 mm. He found that UPV decreased as replacement ratio increased (Girskas & Nagrockiene, 2017).

In same vein, Issa and Salem (2013) tried crumb rubber as fine aggregate to substitute by weight in amounts of 0, 5, 10, and 15%, with sizes of 4.75 mm. He found that UPV decreased as replacement ratio increased (Issa & Salem, 2013).

Likewise, Jafari and Toufigh (2017) tried crumb rubber as fine aggregate to substitute by weight in amounts of 0, 10, 20, and 30%, with sizes of 4 mm. He found that UPV decreased as replacement ratio increased (Jafari & Toufigh, 2017).

Chapter 3

EXPERIMENTAL PROGRAM

3.1 Introduction

Within this chapter, a program was intended to achieve the points of the research. This included sourcing for constituent materials, review and examination of these materials, care and handling, preliminary mixing, perception and testing of concrete as fresh, perception and testing of the concrete when hard, lastly, non-destructive tests. The detailing of results was finished with Excel, and different devices. It follows in the next chapter. A flowchart is attached to show the process taken from curating the plan to definite completion.

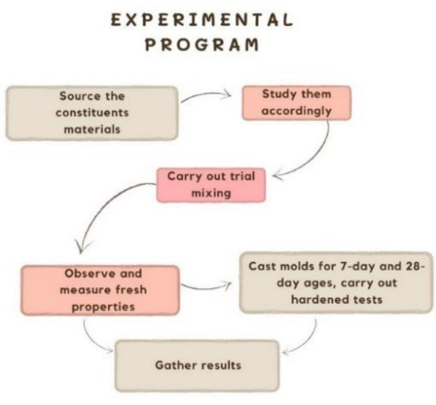


Figure 3.1: Experimental program flowchart

3.2 Materials

The constituent materials utilized are: cement, coarse aggregates, fine aggregates, water, and crumb rubber.

3.2.1 Cement

Cement utilized in carrying out this research was CEM II/BS 42.5 N in accordance to EN 197-1 (County Surveyors, 2002).

3.2.2 Fine aggregates

Crushed limestone rock of mainly sizes 2.36 to 0.075 mm acquired from narrows behind Materials of Construction Laboratory at the Civil Engineering Department was utilized.

3.2.3 Coarse aggregates

Crushed limestone rock of mainly sizes 6.30 to 20 mm obtained from bay behind Materials of Construction Laboratory at the Civil Engineering Department was used.

3.2.4 Crumb rubber

Crumb rubber aggregates of sizes conforming to fine crushed rock were obtained from factory outside Famagusta.

3.2.5 Water

Potable water is used to mix concrete. This was obtained from the Materials of Construction Laboratory at the Civil Engineering Department.

Figure 3.2: Constituent materials of concrete for this research

Table 3.1: Physical tests on constituents

Aggregate Type / Property	Coarse Aggregates	Fine Aggregates	Crumb rubber
Specific Gravity	2.73	2.75	1.25
Moisture Content	0.40%	2.17%	0.06%
Absorption capacity	0.73%	1.57%	Negligible
Bulk density	1370.16 Kg/m^3 for loose, 1489.13 Kg/m^3 for compacted		

3.3 Tests for aggregates

All aggregates utilized were tested to decide their physical properties. These included sieve examination, moisture content, specific gravity and absorption, and bulk density.

3.3.1 Particle size distribution

This test method matters to evaluate materials intended for use as aggregates. The outcomes decide particle size distribution compliance in line with specific determinants that apply, and offering guide that is needed to sway over aggregates production of varying sizes, plus the mixture that contain aggregates. The information obtained also relates to porosity and packing. It can decide different physical properties. The aides utilized are ASTM C136, ASTM C33. The necessary hardware is Balance, Sieves, Mechanical Sieve Shaker, and Oven.

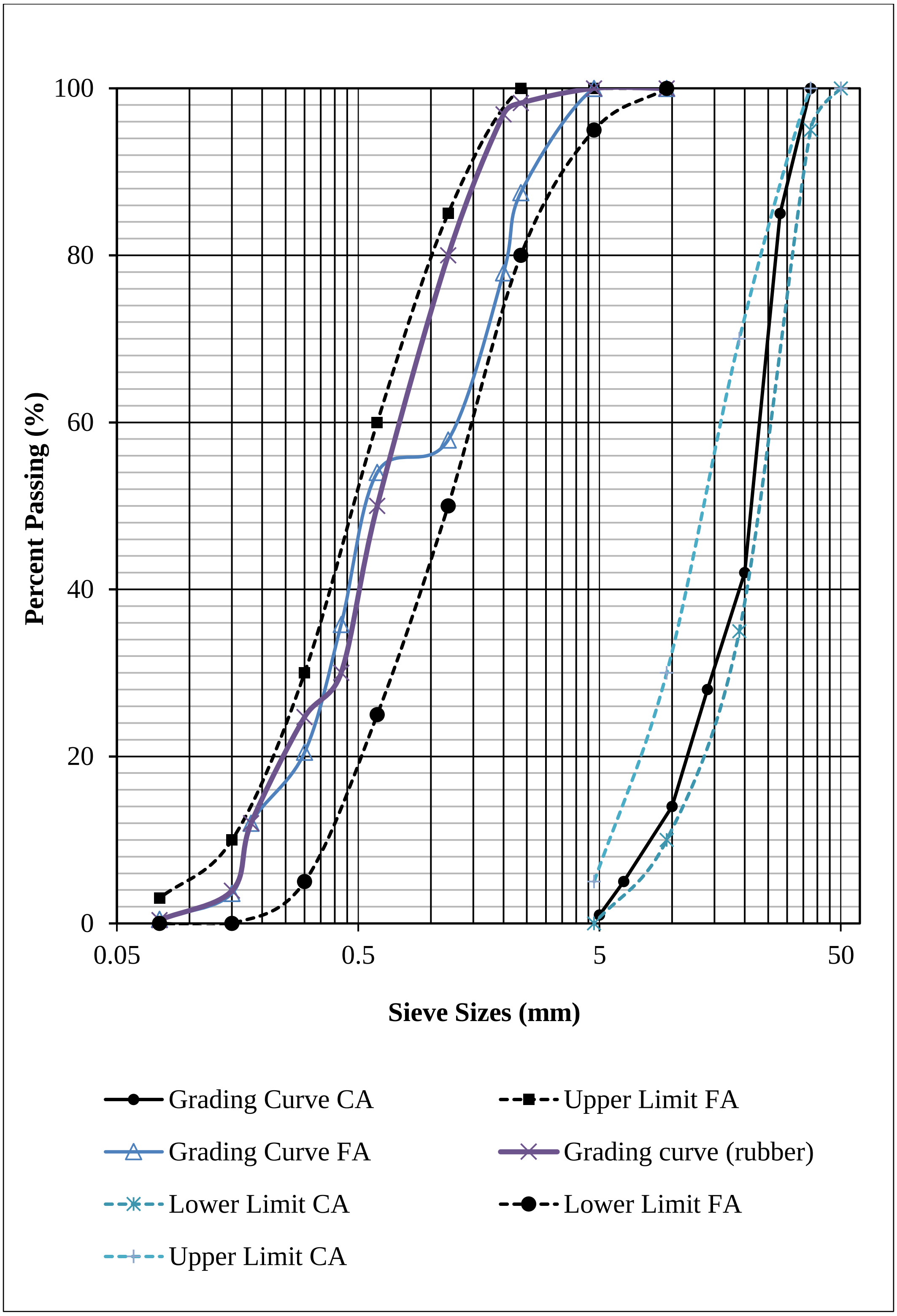


Figure 3.3: Particle size distribution of aggregates

In the chart, Figure 3.3 above, the results of cumulative percent passing through sieves according to Tables 3.2-3.5 below, are plotted.

Table 3.2: Coarse aggregates sieve analysis

Sieve No.	Sieve desc. (mm)	Weight retained (g)	Cumulative wt. retained (g)	Percent retained (%)	Cumulative percent retained (%)	Cumulative percent passing (%)
N/A	37.5	-	-	-	-	100.00
N/A	28	300.00	300.00	15.00	15.00	85.00
N/A	20	860.00	1160.00	43.00	58.00	42.00
N/A	14	280.00	1440.00	14.00	72.00	28.00
N/A	10	280.00	1720.00	14.00	86.00	14.00
N/A	6.3	180.00	1900.00	9.00	95.00	5.00
N/A	5	80.00	1980.00	4.00	99.00	1.00
Pan	N/A	20.00	2000.00	1.00	100.00	-
Total Wieght Retained (gr)		***2000.00***				
Total Sample Size (gr)		***2000.00***				

Table 3.3: Fine aggregates sieve analysis

Sieve No.	Sieve desc. (mm)	Weight retained (g)	Cumulative wt. retained (g)	Percent retained (%)	Cumulative percent retained (%)	Cumulative percent passing (%)
318	9.5	-	-	-	-	100.00
#4	4.75	-	-	-	-	100.00
#8	2.36	61.13	61.13	12.50	12.50	87.50
#10	2	46.94	108.07	9.60	22.10	77.90
#16	1.18	97.80	205.87	20.00	42.10	57.90
#30	0.6	19.07	224.94	3.90	46.00	54.00
#40	0.425	89.00	313.94	18.20	64.20	35.80
#50	0.3	74.82	388.76	15.30	79.50	20.50
#80	0.18	41.57	430.33	8.50	88.00	12.00
#100	0.15	41.08	471.41	8.40	96.40	3.60
#200	0.075	15.16	486.57	3.10	99.50	0.50
Pan	N/A	1.96	488.53	0.40	99.90	-
Total Wieght Retained (gr)		***488.53***		**FM =**	**2.77**	
Total Sample Size (gr)		**489.02**				

Table 3.4: Crumb rubber sieve analysis

Sieve No.	**Sieve desc. (mm)**	**Weight retained (g)**	**Cumulative Wt. retained (g)**	**Percent retained (%)**	**Cumulative percent retained (%)**	**Cumulative percent passing (%)**
318	9.5	-	-	-	-	100.00
#4	4.75	-	-	-	-	100.00
#8	2.36	5.98	5.98	1.76	1.76	98.24
#10	2	4.66	10.64	1.37	3.13	96.87
#16	1.18	57.36	68.00	16.87	20.00	80.00
#30	0.6	101.97	169.97	29.99	49.99	50.01
#40	0.425	68.00	237.97	20.00	69.99	30.01
#50	0.3	17.98	255.95	5.29	75.28	24.72
#80	0.18	43.25	299.2	12.72	88.00	12.00
#100	0.15	27.44	326.64	8.07	96.07	3.93
#200	0.075	12.00	338.64	3.53	99.60	0.40
Pan	N/A	1.36	340.00	0.40	100.00	-
Total Wiegth Retained (gr)		***340.00***		**FM**	**2.43**	
Total Sample Size (gr)		***340.00***				

From the aggregates sieve analysis shown in Figure 3.3, and Tables 3.2-3.4, the aggregates were used accordingly in the following ratios depicted in Table 3.5 below.

Table 3.5: Aggregates mix ratio

Aggregate types	Fine Aggregates		Crumb rubber		Coarse Aggregates			
Sizes	<600 microns	>600 microns	<600 microns	>600 microns	6.30 mm	10 mm	14 mm	20 mm
Ratio	1	1	1	1	1	1.5	1.5	4

3.3.2 Moisture content

This method of testing is competently proper for normal reasons, such as changing set amounts of elements for concrete mixtures. It covers the estimation of able-to-lift moisture percentage in a collection of aggregates by heating the moisture surface, and moisture in the aggregate pores. The aides utilized are ASTM C566. The necessary hardware is Balance, Oven, Container.

Figure 3.4: Aggregates in the oven for moisture content

3.3.3 Specific gravity (fine aggregates)

The mass-mass of an aggregate when compared to its equivalent water volume. same as the aggregate particles - likewise alluded to as the outright aggregate volume, is known as relative density (specific gravity). Additionally, it is the ratio of the density of the aggregate particles, to the density of water. In this test method, the estimation of relative density (specific gravity), and the absorption of fine aggregates is covered. The relative density (specific gravity), a quality of no dimensions, and it can either be oven-dry (OD), soaked surface-dry (SSD), or as obvious relative density (specific gravity). The aides utilized are ASTM C128. The necessary gear is Balance, Pycnometer (for application with gravimetric procedure), mold and tamper (for surface moisture test), Oven.

Figure 3.5: Specific gravity of fine aggregates in action

3.3.4 Specific gravity (coarse aggregates)

The aggregate mass, to the mass of a volume of water, in ratios; and in proportion that equals the volume of aggregate particles - likewise alluded to as the outright volume of the aggregate, is known as its relative density (specific gravity). Aggregate relative density can impact by and large strength of concrete comparatively. The aides utilized are ASTM C127, ASTM C33. The necessary hardware are Balances, Sample Container, Water tank, Sieves, oven, basket.

3.3.5 Specific gravity (crumb rubber)

Specific gravity of this unfamiliar material (crumb rubber) will illuminate us on how effectively bonding will occur with the remainder of concrete constituents. This applies to the blend proportioning of concrete. The aides utilized are ASTM C188. The necessary hardware is Le Chatelier flask, funnel, bath, oven.

Dry a sample of crumb rubber to constant mass. Dry the inner parts of the flask with warm air. Level the flask with kerosene, to a point within the 0 and 1-ml mark. Note this. Record the mass of kerosene and flask as Ma. To some degree submerge the flask in water with the guide of a clamp, and record the new lamp oil level. Introduce 25g of crumb rubber slowly into the flask. Record new mass as Mt. The ratio of Mt-Ma, to the change in level of lamp oil prior to embedding the crumb rubber is the density of crumb rubber. This density with w.r.t. the density of water i.e., the weight of crumb rubber in a given volume, to the weight of water in similar volume, provides us with the specific gravity of this crumb rubber (ASTM, 2017).

Maintain the flask to some extent submerged in water shower to stay away from temperature varieties more prominent than 0.2°C.

3.3.6 Bulk density

To decide bulk density, we use this test methods. It is common for selecting extents for concrete mixtures. It covers the estimation of bulk density ("unit weight") of aggregate when compacted or loose, and measured blanks that exist side-by-side with particles in fine, coarse, or mixed aggregates in view of a close assurance. This test applies to clumps that are not bigger than 125mm [5 in.] in ostensible greatest size. The aides utilized are ASTM C29. The necessary gear are balances, tamping rod, measure, thermometer.

Table 3.6: Mix Design

Specimen	w/c ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Crumb rubber (kg/m^3)	Coarse aggregates (kg/m^3)
Control	0.41	237.50	580.00	578.90	(-)	985.60
10-CR	0.41	237.50	580.00	521.01	57.89	985.60
20-CR	0.41	237.50	580.00	463.12	115.78	985.60
30-CR	0.41	237.50	580.00	405.23	173.67	985.60
40-CR	0.41	237.50	580.00	347.34	231.56	985.60

3.4 Concrete mix proportioning

Concrete mix design was obtained by the BRE Design method (See Appendix A). Table 3.6 above outlines the proportions of concrete constituents.

(A) Preparation of Materials. Temperature –Concrete materials were brought to temperature that are ambient within 20 to 30°C [68 to 85F], before mixing the concrete. Properties of these materials are studied under laboratory conditions according to procedures previously outlined, to correct mix design appropriately. I stored the cement inside the laboratory, away from moisture, and on pallet, away from the cold floors. Large frustum bins were used to store the coarse aggregates in the laboratory according to the individual size fractions in my mix designs. Fine aggregates were stored under shed in small open heaps. Crumb rubber aggregates were stored in grain bags under shed.

(B) Mixing and placing concrete. The concrete drum mixer used in this research is a Bentoneira 125L with rating; V~230, Hz~50, KW~0.90, A~3.2. Other necessary equipment includes molds (cube and rectangular prisms), vibrating table, metal tray, scoop.

The procedure for mixing was according to Marar et al. (2016); Marar et al. (2011), and ASTM C192 as thus: Mixer was turned on and kept rotating, then coarse aggregates are dumped in, and tilted to about 60° and allowed to rotate for 1 min, followed by fine aggregates for another 1 minutes, then cement for another 1 minute; finally, water is added, tilting angle is lowered about 5° more, and allowed to rotate for 5 mins before emptying into the tray. Total mixing time stood at 8 minutes. The table below shows a breakdown of specimens cast.

Vibration was done with the aid of vibrating table and set aside for some time before transferring to the curing rooms. The curing room is in accordance to ASTM C192. These specimens are labelled and are transferred to the curing tank. Hardened tests were conducted after 7-day, and 28-day ages.

Figure 3.6: Demolded specimens of 20-CR in the tank; inset, tank is being filled with water using hose to start curing

Moist room was kept locked and dark after leaving it. Mixer and all other equipment were thoroughly cleaned including mixing area, after use.

3.5 Tests for fresh concrete

The following tests were employed to measure concrete workability, consistency, amount of air, and fresh density.

3.5.1 Slump tests

This test is targeted at deciding slump of plastic hydraulic-cement concrete. Why do a concrete slump test? Understanding the consistency of your concrete blend is valuable because of multiple factors. Basically, it allows you to preview what your concrete will resemble before it sets, allowing you to make acclimations to the blend to create a superior product with better consistency. It can likewise bring up defects in a concrete blend. The aide utilized is ASTM C143. A portion of the necessary hardware include: Slump cone (with base and clamps), tamping rod, glass ruler, scoop.

Figure 3.7: Slump test setup

3.5.2 Vebe consistometer tests

The Vebe Consistometer is utilized to decide the consistency of fresh concrete by subjecting the concrete specimen to vibration after evacuation of the slump cone. The gathering is mounted upon a little vibrating table working at a proper sufficiency and frequency. An opportunity to complete the expected vibration gives an indication of the concrete consistency. The Vebe tests can decide how the concrete will act during compaction. It is likewise especially valuable for estimating samples that might be too solid to be in any way measured by a standard slump test. The guides used are ASTM C1170, Marar et al. (2011) (Marar & Eren, 2011; ASTM, 2020). The necessary equipment used are Vebe Consistometer, tamping rod, stopwatch, scoop.

Figure 3.8: Vebe test setup

3.5.3 Air content tests

This is the evaluation of fresh concrete by the amount of air in it. The testing can measure air content in concrete of fresh mix, without air that lives in aggregate pores. Thus, it applies for the most part to concrete with somewhat dense aggregates. This is utilized in the site to grasp the weight of concrete, decide voids, and characterize a batch. The aides utilized is ASTM C231. The necessary gear is Type B Air Meter, Tray, cover assembly, wash bottle, scoop, tamping rod, hammer, strike-off bar.

3.5.4 Unit weight tests

The Unit weight tests are a valuable mechanism in measuring the yield of a concrete batch, and its air content. The Unit Weight is utilized in site conditions to track the development of materials in with the general mish-mash. The aide utilized is ASTM C138. The necessary gear is type B air meter, scoop, tamping rod, scale, strike-off bar.

3.6 Tests for hardened concrete

Different tests on hardened concrete are finished to guarantee the plan strength, and nature of concrete construction is achieved. In this research, we tested the concrete for compressive, split-tensile, and flexural strength; additionally, permeability, water absorption, and heat degradation were analyzed according to the means illustrated below.

3.6.1 Compressive strength

The strength of hardened concrete, as estimated by the compression test, which involves crushing a shape of concrete in a compression testing machine; is known as its compressive strength. It tests the capacity of concrete to withstand a heap prior to experiencing failure. The aides utilized is ASTM C39. The necessary hardware is Compression and flexural testing machine.

Figure 3.9: 150 mm cube subjected to compression load

3.6.2 Split-tensile strength

The basic thought of a tensile test is to place a sample of a material between two installations called "grasps" which clamp the material. The material has known aspects, similar to length and cross-sectional area. Weight is then applied to the material held at one end, with the opposite end fixed. Split-tensile strength is applied to develop structural lightweight concrete members in consciousness of the shear-resist ability they can provide, and to decide the improvement in length of reinforcement. The aides utilized is ASTM C496. The necessary hardware is Brazilian Steel- frame, Compression and flexural testing machine.

(a) (b)

Figure 3.10: (a) side view, (b) control concrete subjected to split-tension load

3.6.3 Flexural strength

This test method deals with flexural strength of concrete by the use of a basic beam with third-point loading. This applies to beams, cantilever, and shafts. The aide utilized is ASTM C78. The necessary gear are Compression and flexural testing machine, ruler guides.


Figure 3.11: beam specimen subjected to flexural load

3.6.4 Elevated temperatures

Imperviousness to fire of structural members is dependent on the heat capacity and mechanics of constituent materials and these properties differ as a function of temperature. Currently, there are restricted state sanctioned test procedures for assessing warm and mechanical properties of construction materials at elevated temperatures. However, noticing concrete conduct on openness to elevated temperature for a controlled time frame is necessary. This will give great reason for investigation, considering plan capacity, and actual performance on openness to fire. This gives prediction of concrete way of behaving at uplifted temperatures. According to Izadifard et al. (2021), procedure is gotten to carry out heat degradation in this research (Izadifard, Khalighi, Moghadam, & Pirnaeimi, 2021). The necessary hardware is Oven - 100°C, Oven - 200°C, gloves.

Figure 3.12: Cubes put in oven for degradation

3.6.5 Permeability tests

The main concept is to measure water penetration profundity after some time, or simply water penetration profundity. Water permeability of concrete is utilized to indicate its durability. The aides utilized are EN 12390-8. The necessary hardware is Concrete Permeability Device (three cell model), spanners, compression-flexural testing machine, rule.

Figure 3.13: Permeability setup

3.6.6 Rate of water absorption

This testing is useful in fostering information expected for relations between concrete mass and volume. It can play very well to decide conformity, with standards that are meant for concrete, to show alterations from one point to the other, within concrete mass. The pace of water absorption tests decides the water absorption rate (sorptivity) of both the external and internal concrete surfaces. The guide used is ASTM C642. The necessary gear is Scale, Hanger, Oven, Plastic box, Bin, Boiler, Weighing Balance with stand.

According to ASTM C642-21, the formulas are as follows:

Absorption after immersion and boiling, % = [(C-A)/A] x 100 (1)

Volume of permeable pore spaces (voids), % = (C-A) / (C-D) x 100 (2)

Where;

A = mass of oven-dried sample, g

B = mass of surface-dry sample after immersion, g

C = mass of surface-dry sample after immersion and boiling, g

D = apparent mass of sample in water after immersion and boiling, g

3.6.7 Non-destructive (pulse velocity) tests

The Ultrasonic Pulse Velocity (UPV), is a common way of testing hardened concrete without destruction, locally referred to as pundit test. The tests measure the time ultrasonic waves permeates through concrete surface sample inversely. The test is performed at 28 days, using the ASTM C 597-16. Using equation (1), we can measure the pulse velocity in this way (ASTM, 2016);

$$\text{Pulse velocity (km/s)} = \frac{\text{Width of concrete (km)}}{\text{Time taken to pass through (s)}} \quad (3)$$

Figure 3.14: Setup of UPV Test
Source: (Borghol, 2018)

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Inception

The results of the preliminary tests, fresh tests, and hardened tests are detailed, in this chapter. The specimens are described as Cont. for control concrete i.e. normal concrete constituents, as in this case, and zero amount of crumb rubber involved; 10-CR for CRC by 10% replacing fine aggregates with crumb rubber; 20-CR for CRC by 20% of fine aggregates replaced with crumb rubber; 30-CR for CRC by 30% of fine aggregates substituted by crumb rubber; and 40-CR for CRC by 40% crumb rubber substituting fine aggregates.

4.2 Crumb rubber effects on fresh properties

Concrete fresh properties of all the mixes were measured with; slump tests, vebe consistometer tests, air content, and unit weight tests.

4.2.1 Crumb rubber consequence on workability

To measure workability, consistency, and mouldability of fresh concrete; we carried out slump cone, and vebe consistometer tests. Other features such as cohesion can be observed when executing these fresh tests.

On examining fresh concrete, control concrete had a collapse in slump, and a tendency to flow. 10-CR had a bit of true slump with bulging around, at the base. 20-CR and 30-CR showed typical true slump, strong cohesion like it could be cut with a knife or scoop. 40-CR had a true slump, and looked like clay lumps.

Figure 4.1: Fresh 40-CR like clay lumps

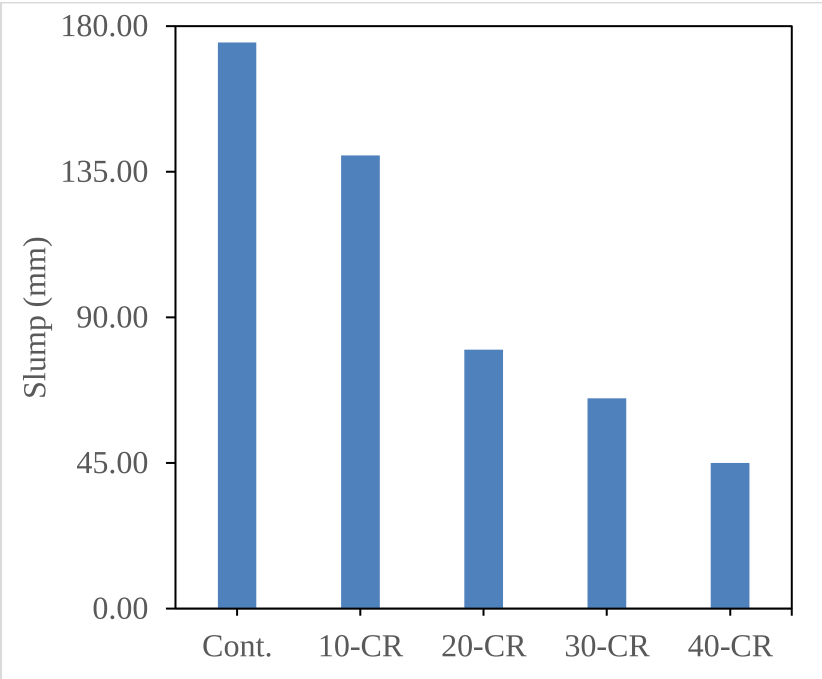


Figure 4.2: Slump of CRC

Crumb rubber reduced workability where superplasticizer was absent (Kumar & Lamba, 2017), just as in Figure 4.2 above. Every 10% increase in crumb rubber reduced slump by averagely 20-30% across all mixes. Majority of the studies have reported decrease in this regard. Some cases were due to crumb rubber attitude to float, particularly in high proportions. These can increase segregation minimally (Yang, Chen, Guo, & Xuan, 2021; Hossain, Shahjalal, Islam, Tiznobaik, & Alam, 2019; AbdelAleem & Hassan, 2019; Onuaguluchi & Panesar, 2014). Attribution of slump reduction, is the roughness of crumb rubber surface in comparison to mineral aggregates (Alsaif, Koutas, Bernal, Guadagnini, & Pilakoutas, 2018). Fine impurities (rubber dust and fluff), and extreme large particles hampered workability (Alsaif, Koutas, Bernal, Guadagnini, & Pilakoutas, 2018; Chen, Li, & Xiong, 2019).

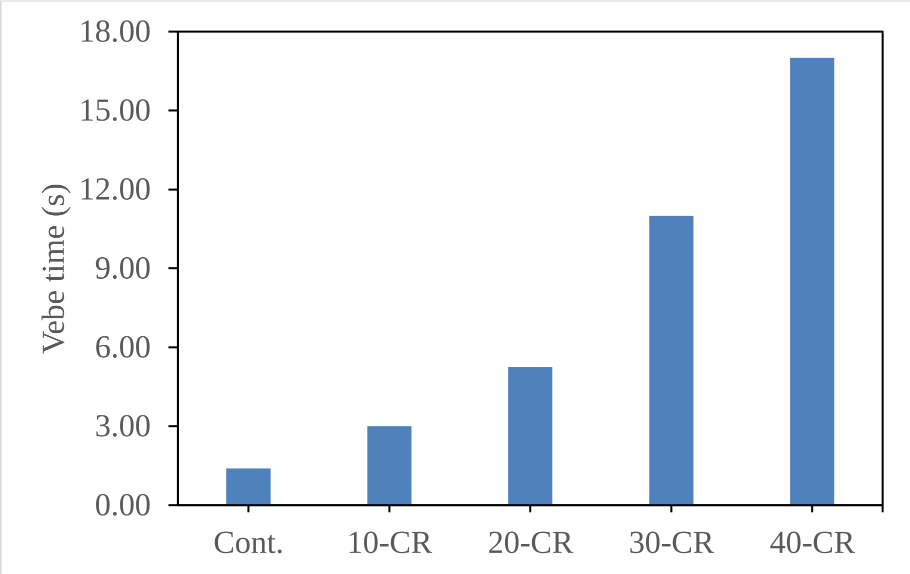


Figure 4.3: Vebe time of concrete mixes

Table 4.1: Vebe consistometer extended results

Parameter	Cont.	10-CR	20-CR	30-CR	40-CR
VeBe slump (mm)	30.00	60.00	55.00	15.00	~
First drop of VeBe rod (mm)	45.00	105.00	75.00	35.00	15.00

In Table 4.1 above, the stickiness of control concrete caused it to attract with the base and walls of the Vebe bucket upholding the mass of concrete from slumping (Marar & Eren, 2011). This resulted in lesser slump than the 10-CR and 20-CR. This further emphasizes the mouldability enhanced by crumb rubber. Raising the glass plate to zero mm height and releasing; control concrete held it up at 45 mm, compared to 105 mm for 10-CR, and 75 mm for 20-CR. This shows that CRC, particularly 10-CR, and 20-CR in this instance, is more pliable than control concrete. The actual cement content in control concrete causes bond of attraction with the glass plate. This reduced the first drop height.

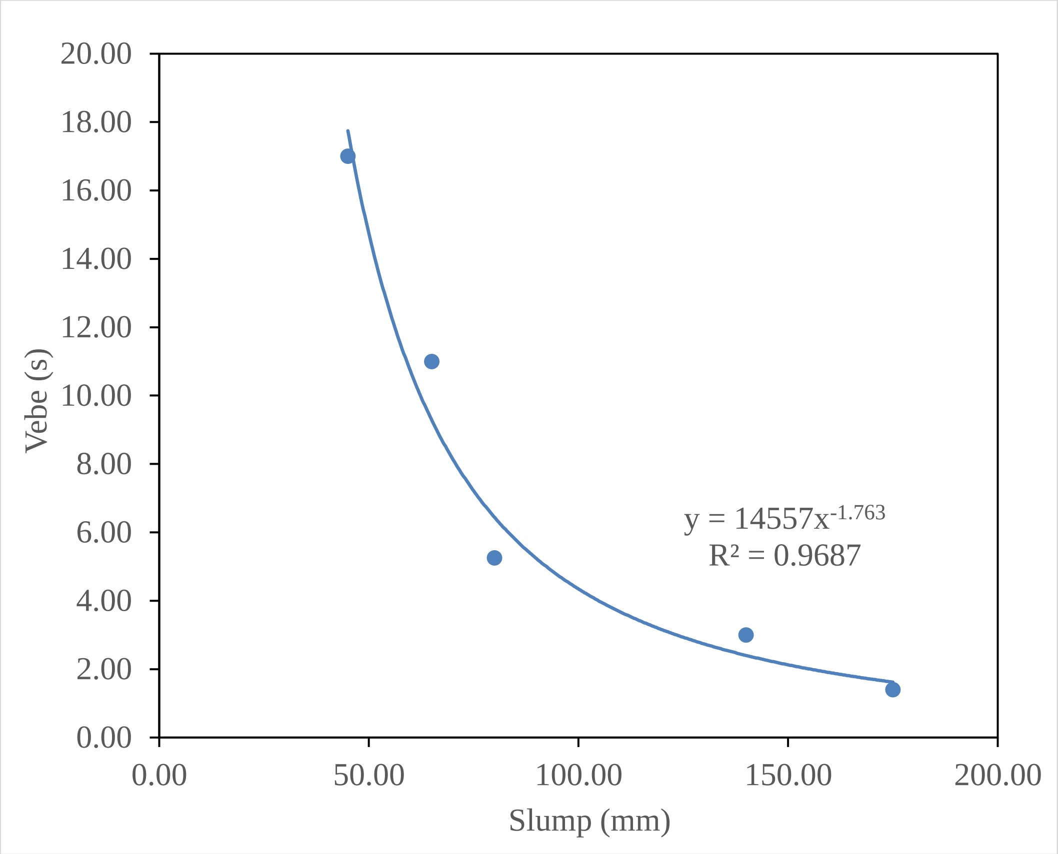


Figure 4.4: Slump and vebe correlation

Similar strong correlation of R^2 = 0.9506 has been reported for relationship between Vebe and Slump, in the literature (Marar & Eren, 2011). In Figure 4.4, Vebe time increased moderately as slump reduced, and steeply after 20-CR.

4.2.2 Cause of crumb rubber on air content

The amount of air in each concrete mix for a size about 8 L was tested using Type B Air meter. In the Figure 4.5 below, air content increased steadily for crumb rubber concrete compared to control (Khatib & Bayomy, 1999). Figure 4.6 showed a proportionate rise in air content by replacement levels. Authors have named the non-polar nature of rubber aggregates as a probable cause of this; coupled with lightly dense rubber aggregates which culminates in lighter unit weight of rubber concrete (Kumar & Lamba, 2017; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021). Crumb rubber has the ability to repel water, attract air, and thus, introduces bubble into the concrete (MUTAR, HUSSEIN, & MALIK, 2018).

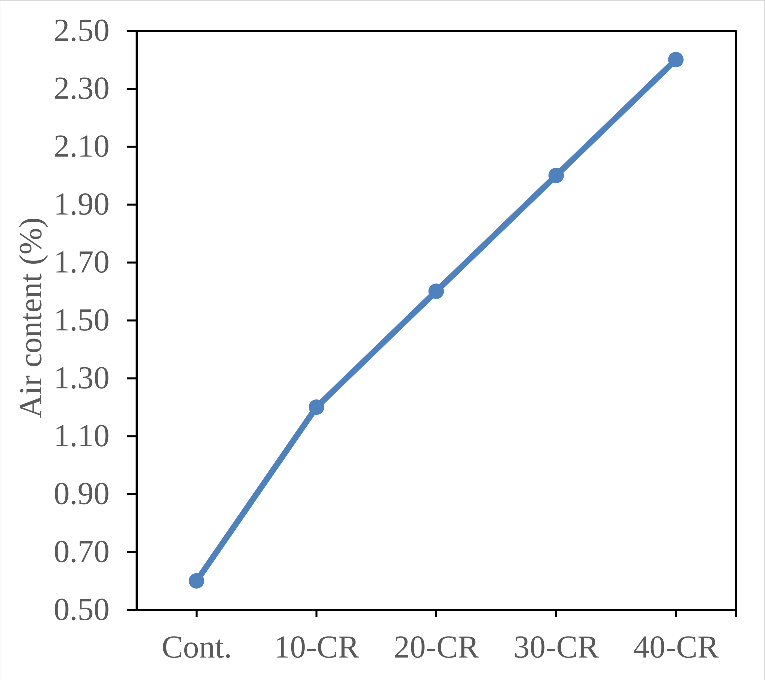


Figure 4.5: Crumb Rubber Concrete (CRC) air content

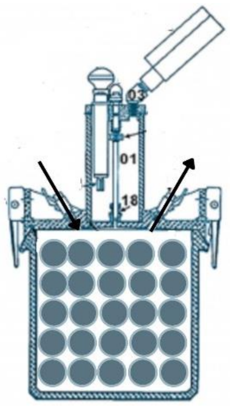


Figure 4.6: Type B air meter

In carrying out these tests, Table 4.7 below shows the volume of water needed to inject and top off, at one petcock till expulsion at the other petcock, as shown by the black arrows in Figure 4.6 above. These lesser parameters are necessary to estimate the percentage of pores in fresh concrete due to crumb rubber addition. Later on in this chapter, Figure 4.37, we get to see the similar results in the case of hardened concrete with crumb rubber.

Table 4.2: Air content tests extended results

volume of water (cm^3) needed to pass through chamber				
Cont.	10-CR	20-CR	30-CR	40-CR
13.73	86.07	172.50	213.03	343.99

4.2.3 Consequence of crumb rubber on unit weight

In Figure 4.7 below, crumb rubber reduced unit weight proportionately by 4-7% at every 10% increase in replacement level. This represents nearly 20% decrease in unit weight from control concrete to 40-CR. Other studies found similar range reductions across varying intervals (Kumar & Lamba, 2017).

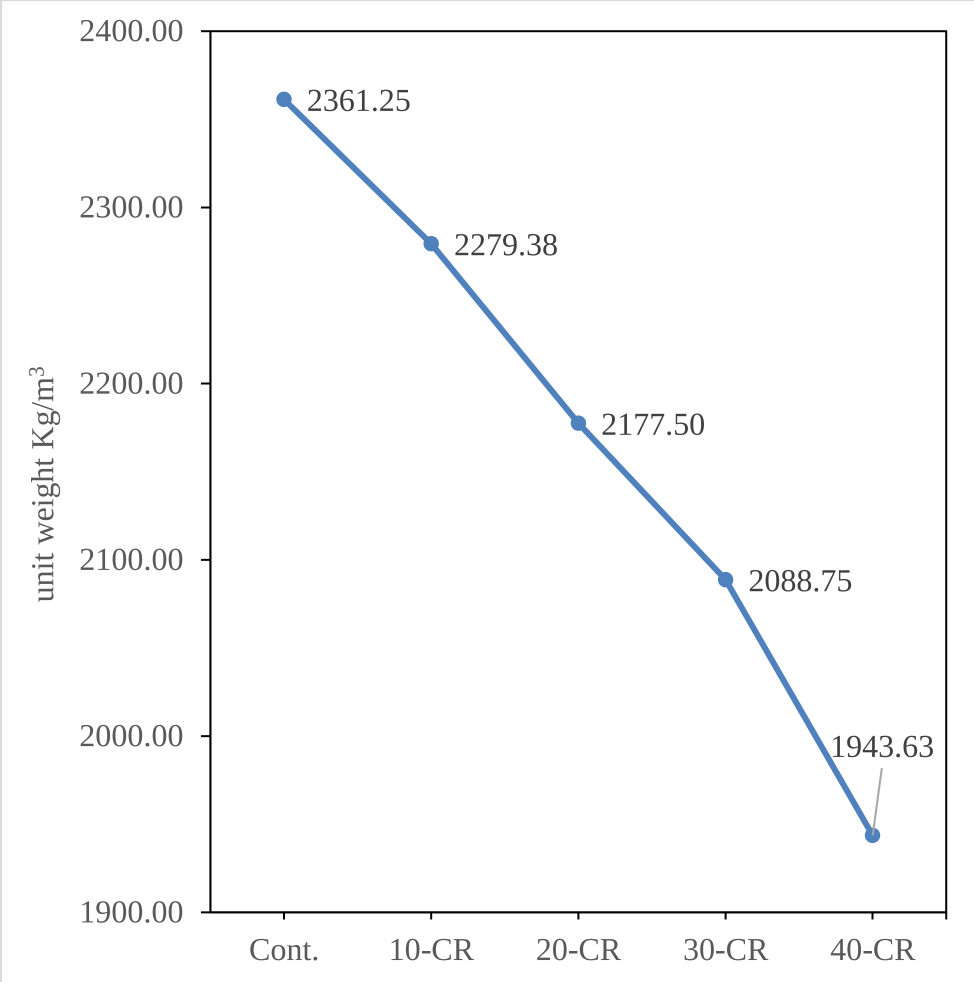


Figure 4.7: Crumb Rubber Concrete (CRC) unit weight

Also, CRC mixes demonstrate a strong relationship between air content and unit weight. This is evidenced in the Figure 4.8 below. Figure 4.8 showed a strong linear correlation of R^2 = 0.9685. Mohammed et al. (2014) discovered similar strong linear correlation of R^2 = 0.9355 for unit weight, and R^2 = 0.9549 for air content, with replacement levels of 0-30% by volume, as independent variable (MOHAMMED & AZMI, 2014).

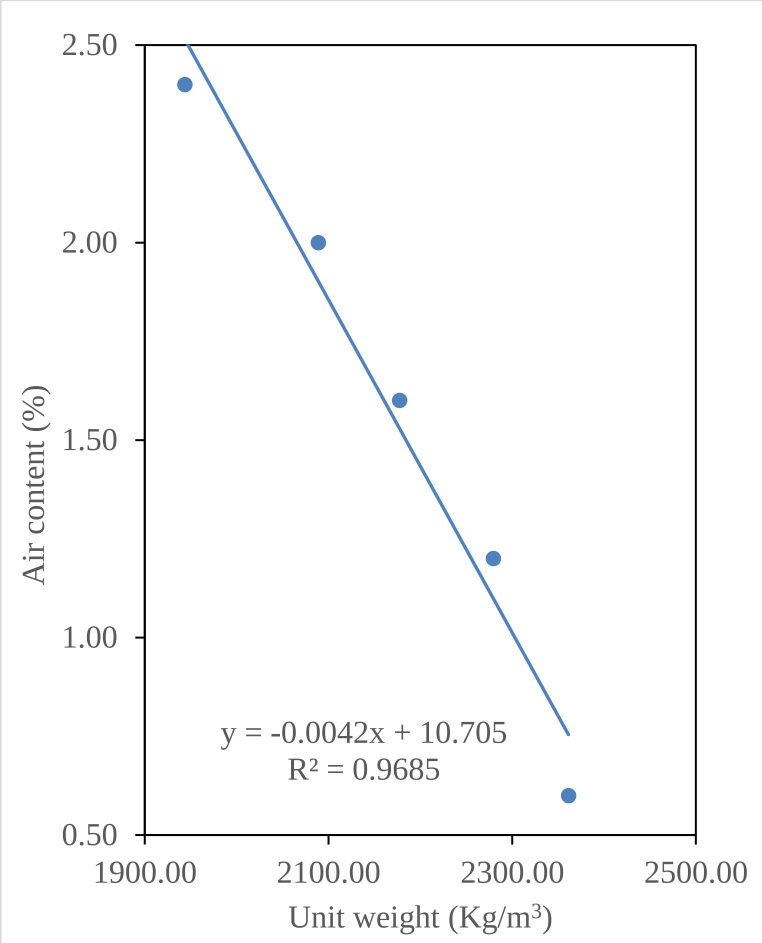


Figure 4.8: Air content and Unit weight of Crumb Rubber Concrete (CRC) Correlation

4.3 Reactions of hardened properties due to crumb rubber

In this section, we discuss the results of the following hardened properties; compressive strength, split-tensile strength, flexural strength, heat degradation, permeability, rate of water absorption, and pulse velocity.

4.3.1 Impressions of crumb rubber on compressive strength

In the Figure 4.9 below, compressive strength fell with the rise in crumb rubber amounts. It is observed that crumb rubber gains much higher strength percentage after 7-days, compared to control concrete. The stunted maturity after 7 days through till 28 days is due to effective cement paste taken up by crumb rubber, within the concrete matrix that continually produce hydration compounds throughout the 28 days of curing. Additional reason is that, compressive strength fell accruing to the replacement of sand with lightly-dense crumb rubber (Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015). Clearly found out in the literature, is the fact that crumb rubber and cement mortar together, produced an ITZ that is nowhere close to the ITZ that occurs between the natural aggregates, and mortar of cement. There is poor state of rigid existence between rubber, and cement particles, and thus, generate regions of top stress concentrations at the ITZ, erupting in crack formation within that zone. This brings about least resistance load deformation link (Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015). Additional validity to this is that, 70% of the cracks that occur in concrete are ITZ cracks. They remain the main point of propagation for cracks in concrete (Department of Civil Engineering, 2014). Figure 4.11 below showed 30-60% reduction in compressive strength, from 10-40% replacement by crumb rubber. This is close to Thomas BS et al. (2014) that discovered 41.2-52.9%, 44.9-48.7%, and 49.9-53.4% reduction; for w/c ratios of 0.3, 0.4, and 0.5, for 15-20% replacement by weight of FA with CR and rubber powder (Thomas B. , Gupta, Kalla, & Cseteneyi, 2014). Angelin AF et al. (2022) recorded 69, and 79.2% reduction in compressive strength when replacing FA by weight in ratios of 15, and 30% with 600 microns spheroid rubber particles, and 1.2mm rubber fiber (Angelin, AF; Miranda, EJP; Santos, JMCD; Lintz, RCC; Gatchet-Barbosa, LA, 2019).

Table 4.3: 7-day compressive strength

Mixture Type	Maximum Load (KN)	Compressive Strength (MPa)	Change of compressive strength (%)	Dry Density (Kg/m^3)
Cont.	854.00	37.90	-	2453.33
10-CR	725.00	32.20	-15.04	2349.63
20-CR	441.00	19.60	-48.28	2228.15
30-CR	456.00	20.30	- 46.44	2212.35
40-CR	346.00	15.38	-59.42	2103.70

Table 4.4: 28-day compressive strength

Mixture Type	Maximum Load (KN)	Compressive Strength (MPa)	Change of compressive strength (%)	Dry Density (Kg/m^3)
Cont.	1307.00	58.10	-	2361.48
10-CR	912.30	40.50	-30.29	2295.80
20-CR	633.67	28.20	-51.46	2135.80
30-CR	587.33	26.10	-55.08	2096.30
40-CR	512.33	22.77	-60.81	2163.95

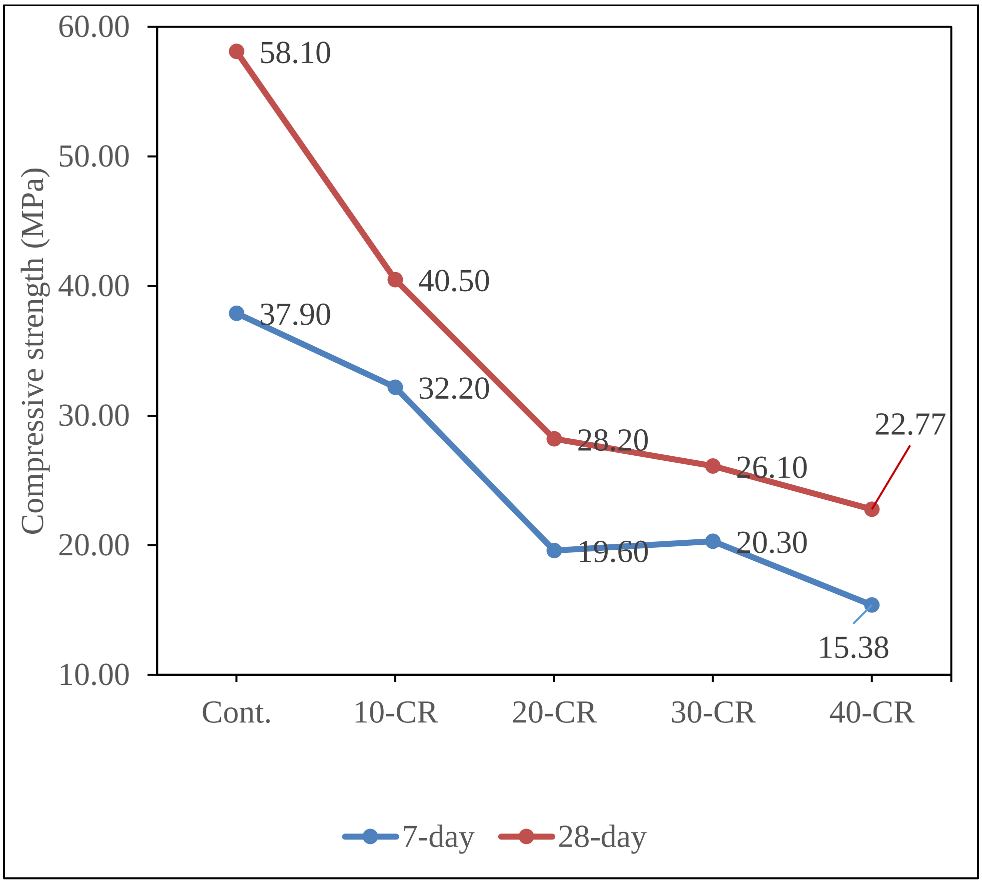


Figure 4.9: Compressive strength of CRC

The Table 4.9, and Figure 4.10 below details like research on Crumb Rubber Concrete (CRC) and results obtained regarding compressive strength.

Table 4.5: Literature comparison of compressive strength percentage relative to control mix

Rubber sizes (mm)	C.S. control mix (MPa)	w/c	Replacement level (%)	Strength percentage relative to the control mix (%)	References
<2	34.1	0.48	0, 25, 50, 75, 100	100, 71.8, 57.8, 44, 37.8	(Eldin & Senouci, 1993)
≤1	29.5	0.62	0, 15, 30, 45	100, 66.8, 56.6, 43.4	(Topcu, 1995)
≤2	33.0	0.53	0, 22.2, 33.3	100, 74.8, 61.2	(Bignozzi & Sandrolini, 2005)
0.85	24.0	0.54	0, 10, 20, 30	100, 67, 50.8, 21.3	(Herrera-Sosa, Martínez-Barrera, Barrera-Díaz, & Cruz-Zaragoza, 2014)
2-4, 0.8-2, dust	42.5	0.4	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	100, 96.5, 88.2, 87.1, 78.8, 70.6, 58.8, 54.8, 47.1	(Thomas B. S., Gupta, Kalla, & Cseteneyi, 2014)
2-4, 0.8-2, dust	39.0	0.45	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	100, 97.4, 84.6, 78.2, 70.5, 64.1, 55.1, 55.1, 51.3	(Thomas B. S., Gupta, Kalla, & Cseteneyi, 2014)
2-4, 0.8-2, dust	36.5	0.5	0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	100, 92.3, 84.1, 80.3, 80.3, 65.8, 58.4, 50.1, 47.9, 46.6	(Thomas B. S., Gupta, Kalla, & Cseteneyi, 2014)
2-4	39.0	0.54	0, 20, 50	100, 78, 70	(Dehdezi, Erdem, & Blankson, 2015)
2-4	30.68	0.5	0, 2.5, 5, 7.5	100, 93.9, 84.1, 70.1	(Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015)

1 - 1.32	39.1	0.52	0, 15, 30	100, 77.2, 54.3	(Rezaifar, Hasanzadeh, & Gholhaki, 2016)
0.6 spheroid & 1.2 fiber	50	0.48	0, 7.5, 15, 30	100, 62.2, 31, 20.8	(Angelin, AF; Miranda, EJP; Santos, JMCD; Lintz, RCC; Gatchet-Barbosa, LA, 2019)
0.4	34.30	0.6	0, 4, 4.5, 5, 5.5	100, 96.2, 88.3, 84.8, 82.2	(Bisht & Ramana, 2019)
2.36 - 0.075	58.1	0.41	0, 10, 20, 30, 40	100.00, 70.00, 48.54, 44.92, 39.19	This research

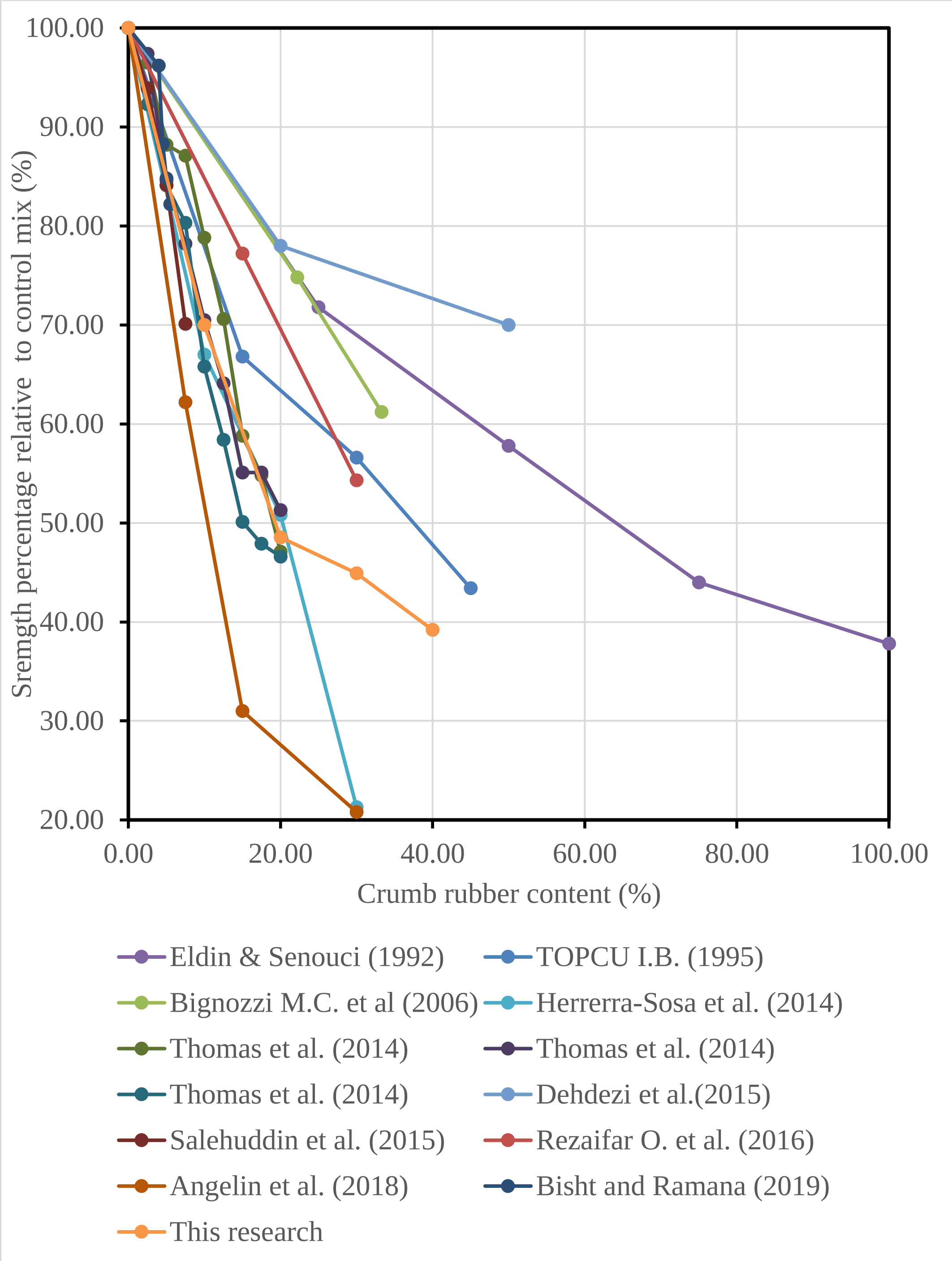


Figure 4.10: Strength percentage relative to compressive strength control mix (%)

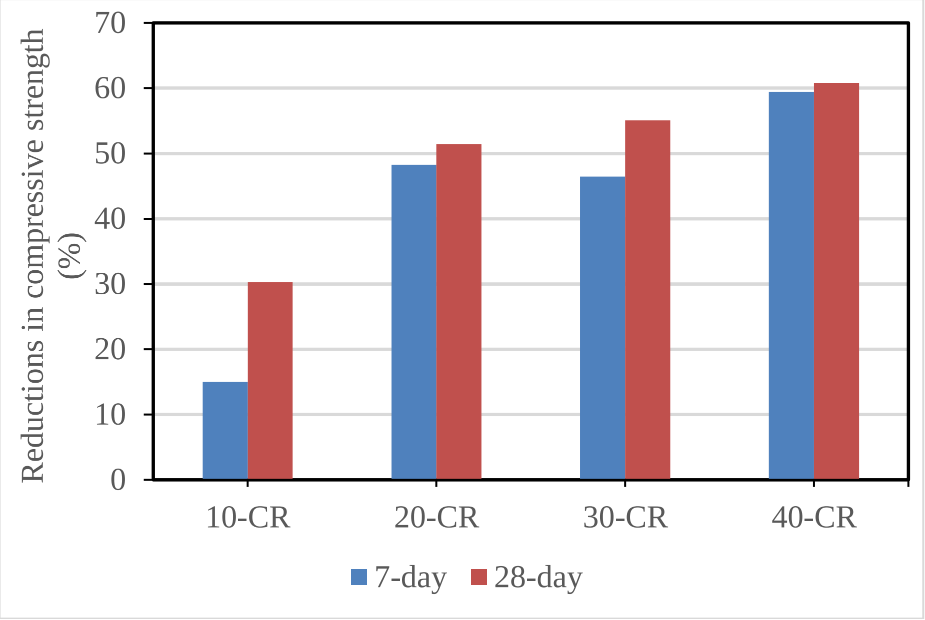


Figure 4.11: Percent reductions in compressive strength

4.3.2 Influence of crumb rubber on split-tensile strength

In Figure 4.12 below, split-tensile strength reduced with crumb rubber replacements, it was above 30% for 10-CR, this is similar to Kumar K. et al. (2017), that discovered 28% reduction in split-tensile strength for 7.5% crumb rubber replacements (Kumar & Ankit, 2017; Assaggaf, Ali, Al-Dulaijan, & Maslehuddin, 2021). Quite obvious during testing, is the non-brittle nature of Crumb Rubber Concrete (CRC).

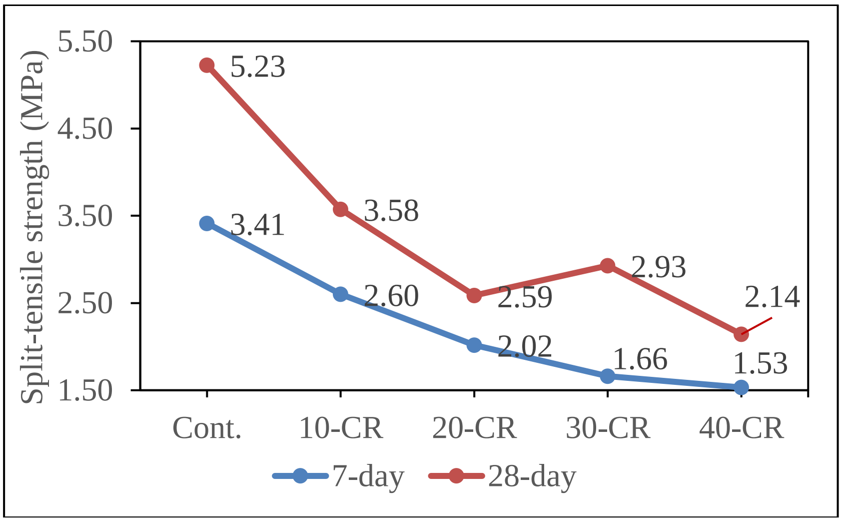


Figure 4.12: CRC split-tensile strength

From Figure 4.13 below, reductions in split-tensile strength ranged from 32-60% for 10-CR to 40-CR. 30-CR however, showed slow maturity in split-tensile strength.

Table 4.6: 7-day split-tensile strength

Mixture Type	Maximum Load (KN)	Split-tensile Strength (MPa)	Change of split-tensile strength (%)
Cont.	120.67	3.41	-
10-CR	92.77	2.60	-23.84
20-CR	71.37	2.02	-40.86
30-CR	58.70	1.661	-51.35
40-CR	54.17	1.532	-55.13

Table 4.7: 28-day split-tensile strength

Mixture Type	Maximum Load (KN)	Split-tensile Strength (MPa)	Change of split-tensile strength (%)
Cont.	184.67	5.23	-
10-CR	126.37	3.58	-31.59
20-CR	91.33	2.59	-50.55
30-CR	103.50	2.93	-43.96
40-CR	75.70	2.14	-59.04

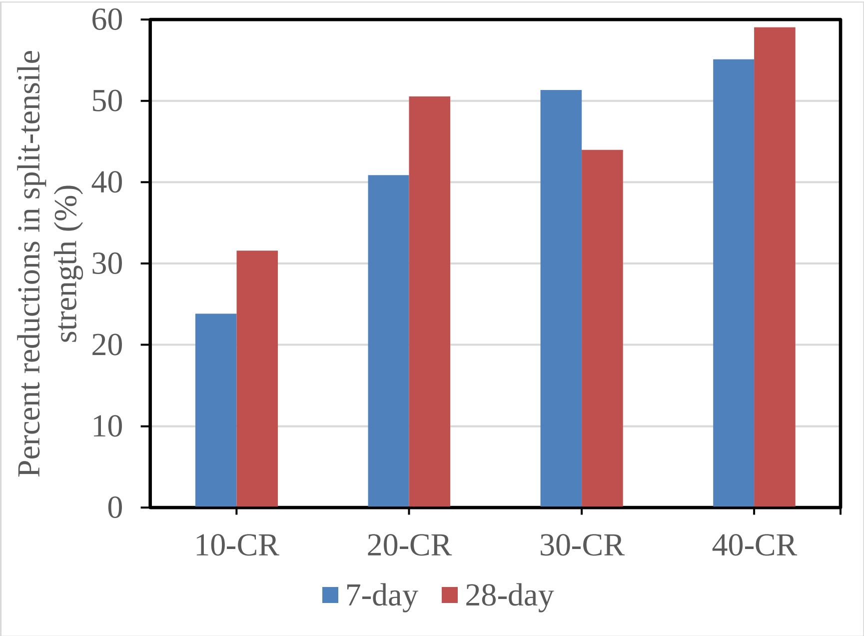


Figure 4.13: Split-tensile strength percentage reductions

4.3.2.1 Link between compressive strength and split-tensile strength

Comparisons were made between split-tensile and compressive strength results at 28 days. The Figure 4.14 below showed strong exponential relationship side-by-side of split-tensile strength and compressive strength and R^2 of 0.9649. S.M.A. Quidi et al. (2021) discovered quite strong polynomial correlation for Crumb Rubber Concrete (CRC) between compressive and split-tensile strength of $R^2 = 0.7195$; for split-tensile strength ranging from 2.5 – 6 MPa, and compressive strength ranging from 15 – 45 MPa (Qaidi, Dinkha, Haido, Ali, & Tayeh, 2021).

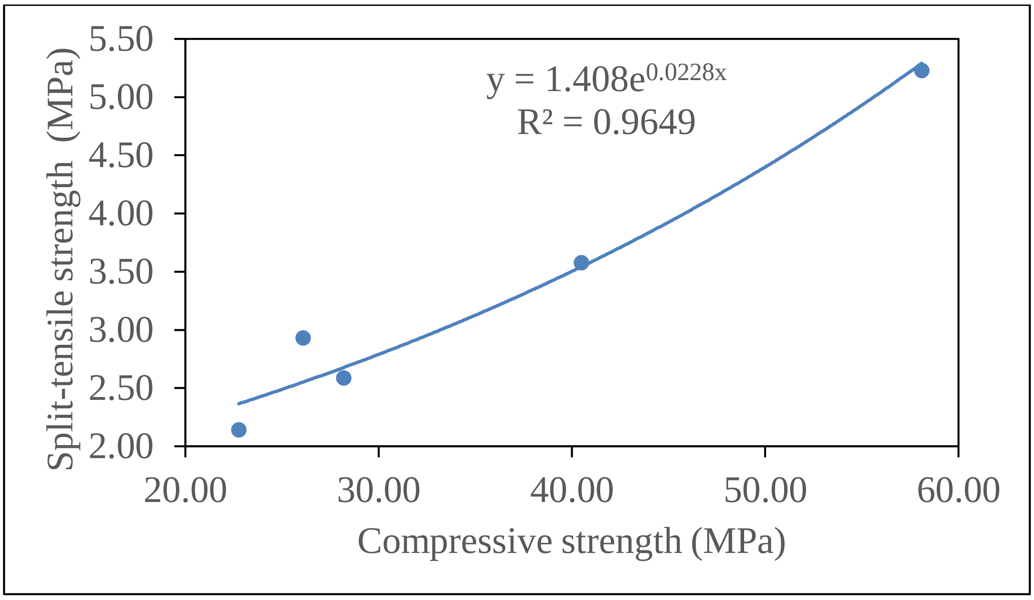


Figure 4.14: Correlation between split-tensile and compressive strength

4.3.3 Footprint of crumb rubber on flexural Strength

Thomas and Gupta (2016) experimented with crumb rubber of groups; one-fourths of 2-4mm, 7/20 of 0.8-2 mm, and two-fifths powdered rubber, replacing fine aggregates by weight in percentages of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20%; with 0.3 w-c/w-b ratio, and control mix of 7.2 respectively. For the mix of 0.3 w/b ratio, he found similar, as in Figure 4.15, but smaller progressive reductions in flexural strength beyond 10%

fine aggregate replacement (Thomas & Chandra, 2016). On testing, there was clear evidence in this research of the flexible nature of Crumb Rubber Concrete (CRC).

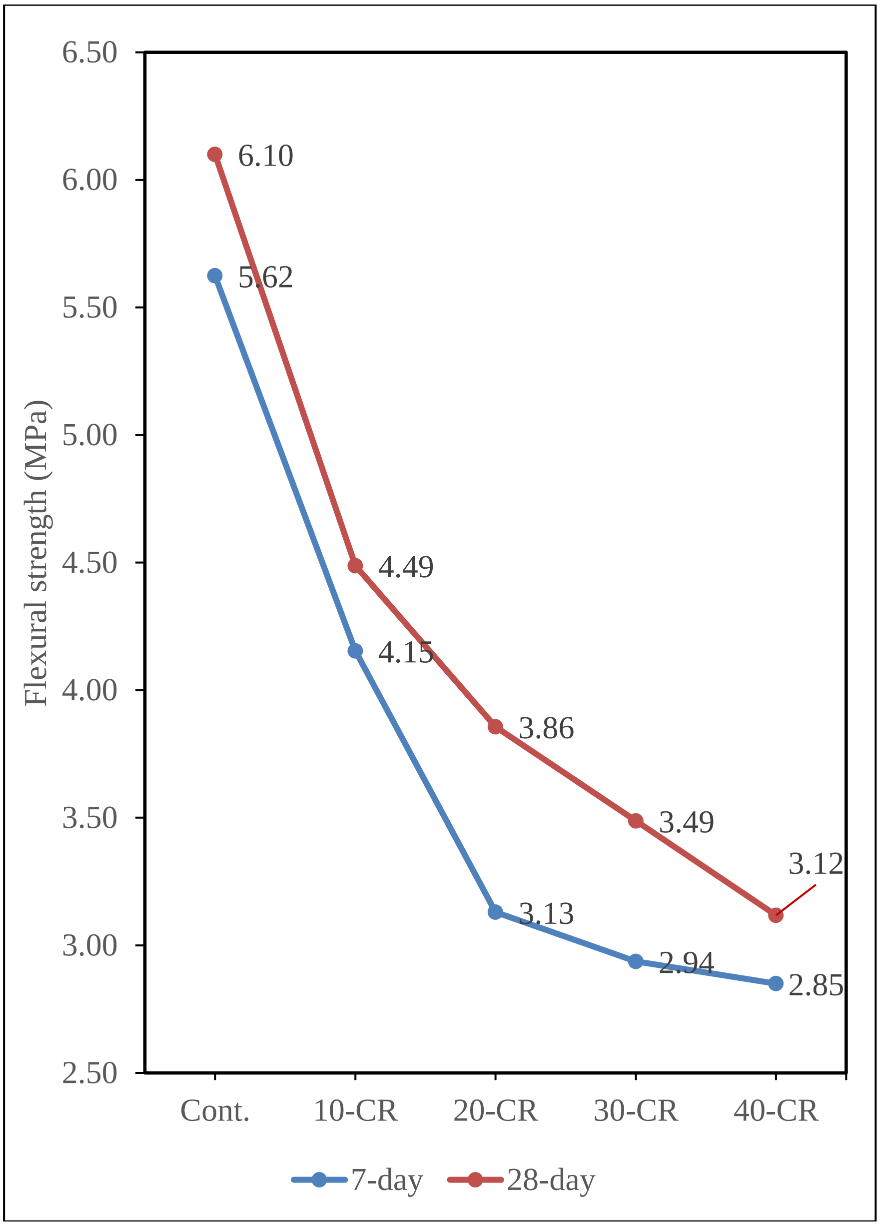


Figure 4.15: CRC flexural strength

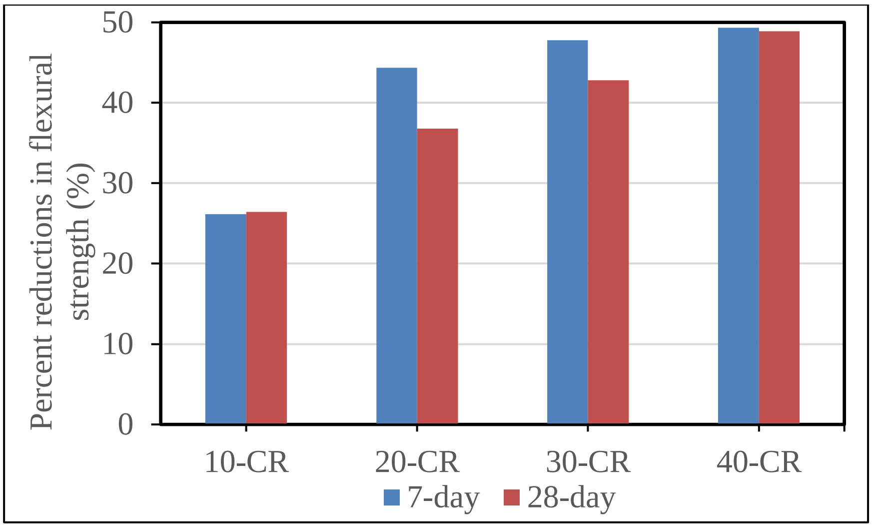


Figure 4.16: Flexural strength percentage reductions

A uniform trend that can be observed here in Figure 4.16 above, is that 28-day flexural strength performed better than 7-days w.r.t to control. Possible explanation for this is that control concrete stunts in growth of bending, it is typical that this may not improve with age.

Table 4.8: Flexural strength at 7 days

Mixture Type	Maximum Load (KN)	Flexural Strength (MPa)	Change of Flexural strength (%)
Cont.	11.23	5.62	-
10-CR	8.33	4.15	-26.14
20-CR	6.27	3.13	-44.35
30-CR	5.90	2.94	-47.78
40-CR	5.70	2.85	-49.32

Table 4.9: Flexural strength at 28 days

Mixture Type	Maximum Load (KN)	Flexural Strength (MPa)	Change of Flexural strength (%)
Cont.	12.25	6.10	-
10-CR	9.00	4.49	-26.43
20-CR	7.73	3.86	-36.77
30-CR	7.00	3.49	-42.82
40-CR	6.23	3.12	-48.89

4.3.3.1 Association between compressive and flexural strength

The flexural strength and compressive strength results at 28 days, were drawn side-by-side. The Figure 4.17 below showed strong linear relation side-by-side of flexural strength and compressive strength, and an R^2 of 0.986. Quidi et al. (2021) discovered quite strong polynomial correlation for Crumb Rubber Concrete (CRC) between Compressive and Split-tensile Strength of R^2 = 0.7815; for Split-tensile Strength ranging from 2.5 – 6 MPa, and Compressive Strength ranging from 15 – 45 MPa (Qaidi, Dinkha, Haido, Ali, & Tayeh, 2021).JU

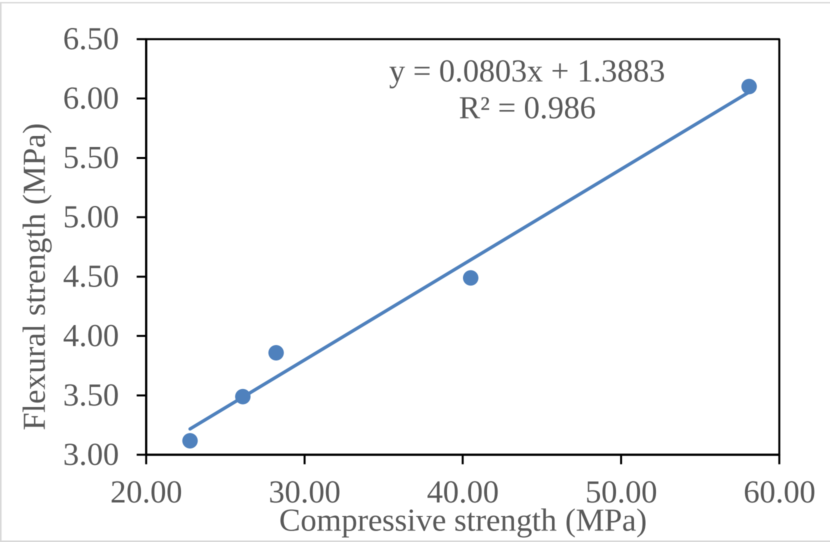


Figure 4.17: 28-day Relationship between flexural strength and compressive strength

There is agreement in the literature between AbdelAleem and Hassan (2019); and Onuaguluchi and Panesar (2014). According to them, silica fume is vital mineral additive to check the drop in flexural strength (Onuaguluchi & Panesar, 2014; AbdelAleem & Hassan, 2019). Additionally, Park et al. (2014) postulated that fibers such as steel, or glass uphold the crack resistance (Park, Abolmaali, Mohammadagha, & Lee, 2014). Aly et al. (2019), Aslani et al. (2020), and Jokar et al. (2019) jointly demonstrated that there is decrease in flexural strength reduction when crumb rubber is pretreated with NaOH (Aly A. , El-Feky, Kohail, & Nasr, 2019; Aslani, Deghani, & Asif, 2020; Jokar, Khorram, & Karimi, 2019; Qaidi, Dinkha, Haido, Ali, & Tayeh, 2021).

4.3.4 Cause of crumb rubber on exposure to heat degradation

Tayebi et al. (2013) discovered that structure strength fell after high temperature exposures. This has been attributed to fast-developing expansion that accompanies the inner pore mechanisms, due to the inability of aggregates that carry light weight to bear, when exposed to high temperatures. Split-tensile strength of CRC reduced in Figure 4.18 below, it degraded more at 100°C, compared to 200°C at 7 days. However, in Figure 4.20 below, at 28 days, they were much alike in degradation. Many authors attribute this to the fact that rubber melts at about 163°C (mostly natural rubber), others say 180°C, they say that this melted rubber binds the concrete matrix and prevents splitting under tensile loads. This is limited to moderate replacement ratios. This emphasizes that CRC can uphold fire at moderate temperatures. Failure and behavior on exposure to tensile loads after heat degradation is milder than control concrete. It implies that concrete thermal conductivity is lowered by crumb rubber. This same view has been upheld in the literature by Paine et al. (2012), Issa and Salem (2013), Paine and Dihar (2010), Mohammed et al. (2012), Hall et al. (2012), Sokkuntasukkul (2009), Pelisser et al (2012), and Faidel et al. (2014). According to them, nearly 50% loss in thermal conductivity is achievable on sand substitution with 10-30% volume or mass, of crumb rubber. This results in improved thermal insulation of concrete owing to crumb rubber. There is some dividedness as to the benefit of porosity in this issue. Some authors state that the reduced density due to porosity of CRC makes it a good material on thermal insulation (Paine, Dhir, Moroney, & Kopasakis, 2012;

Mohammed, Hossaina, Swee, Wong, & Abdullahi, 2012; Hall, Najim, & Hopfe, 2012; Sukontasukkul, 2009; Pelisser, Barcelos, Santos, Peterson, & Bernardini, 2012; Fadiel, Rifaie, Abu-Lebdeh, & Fini, 2014). However, Mahmod M. et al. (2017) states that this porosity can produce massive deterioration in residual strengths after heat degradation. It is therefore advisable to limit replacement ratios of sand with crumb rubber below 30% (Mahmod, Aznieta, & Gatea, 2017).

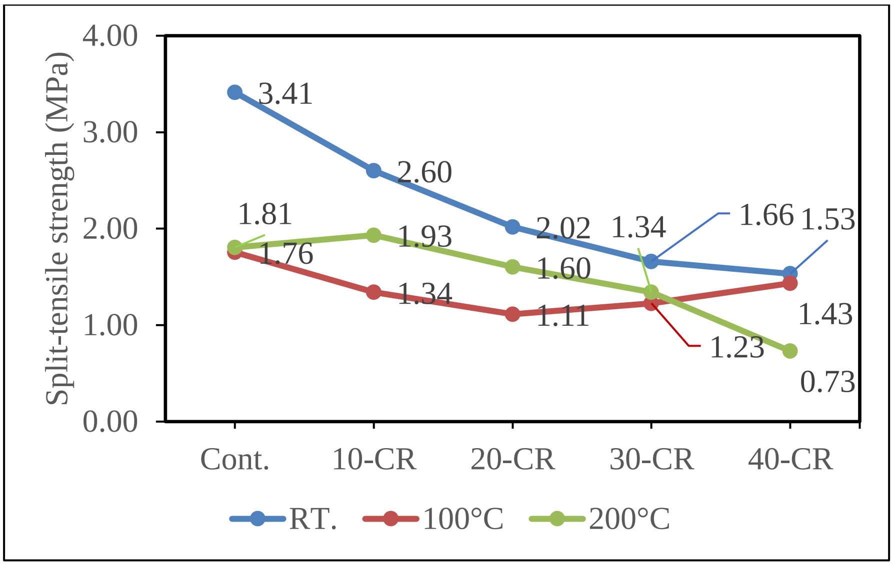


Figure 4.18: 7-day effect of temperature on split-tensile strength

Going by the literature, there is not much study on heat degradation of Crumb Rubber Concrete (CRC). Particularly, exploring reduction in tensile strength after exposure to heat. Some authors have however, explored reduction in compressive strength. The authenticity of this procedure is doubtful, as cracks could be present already within the matrix after degrading by heat. Another issue that comes to fore, is the binding effect of melted and elongated crumb rubber that can improve behavior and resistance to split-tensile, and flexural loads. Hence, in this research, we have opted to observe the potentials of CRC in this regard, after exposure to elevated temperatures. Li Y. et al. (2019) discovered about 33.33, 45, 63.64, and 81.82% loss in compressive strength when subjected to 100°C, for 12 and 24 hr alike; for substitute portions 10, 20, 30, and 40% of crumb rubber by volume (Li, Zhang, & Wang, 2019). In Figure 4.19, the binding effect of crumb rubber caused lesser reductions for 200°C than 100°C in 7-day split-tensile strength. However, at mature ages, in Figure 4.21, reductions in split-tensile strength for 100°C and 200°C were relatively same. Authors in the literature have encouraged testing heat degradation of crumb rubber mostly at room temperature up to 200°C.

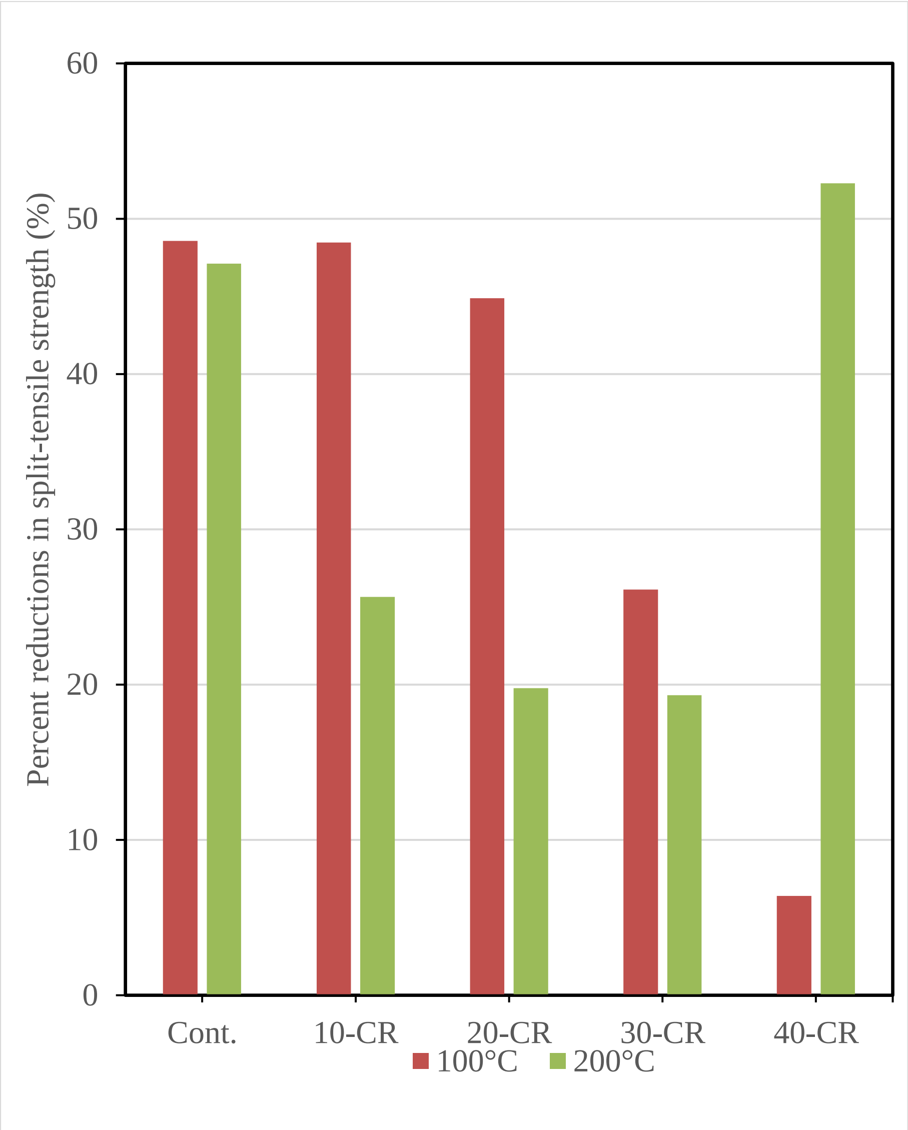


Figure 4.19: 7-day percent reductions in split-tensile strength after heat degradation at 100°C and 200°C w.r.t. room temperature

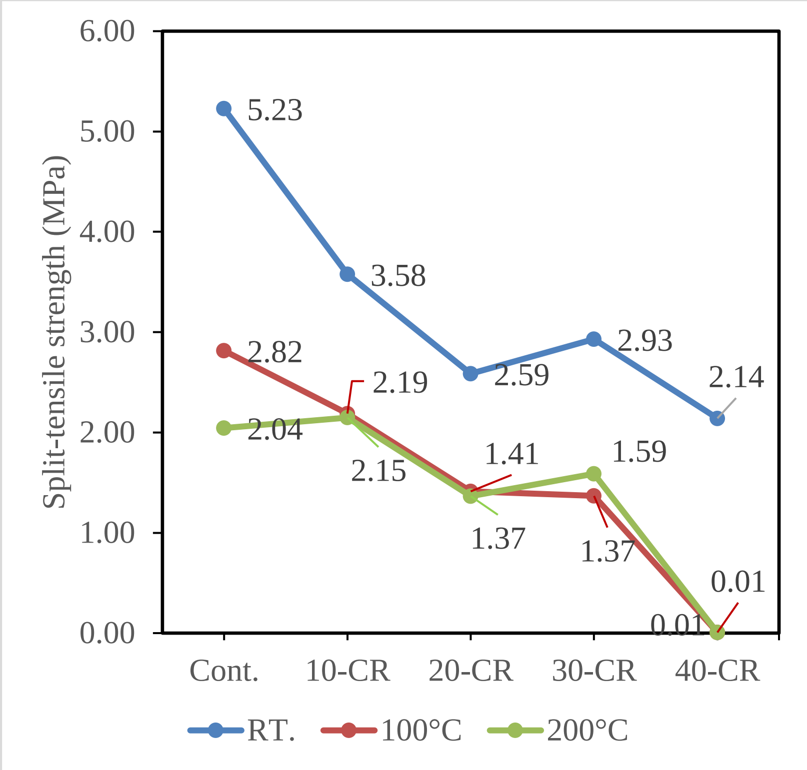


Figure 4.20: Cause of temperature on split-tensile strength after 28-days

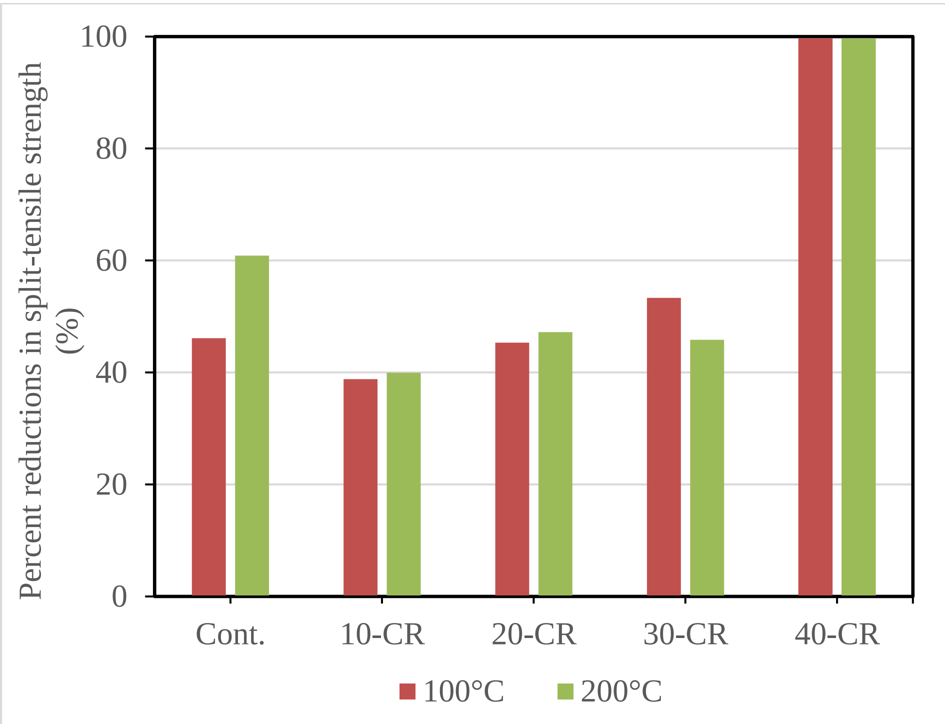
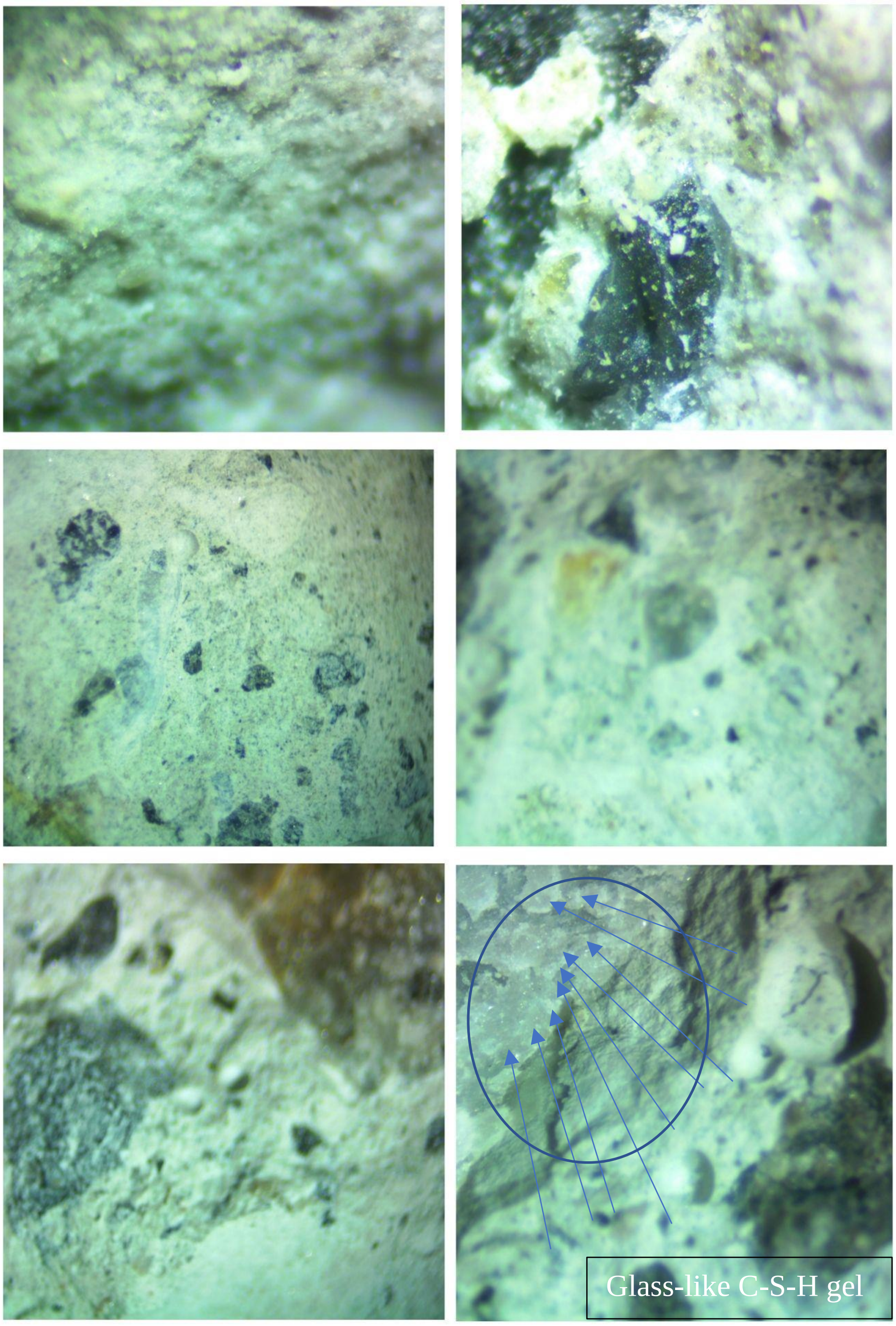


Figure 4.21: 28-day percent reductions in split-tensile strength after heat degradation at 100°C and 200°C w.r.t. room temperature

4.3.4.1 Crack and pores development on exposure to heat

After exposure to elevated temperatures according to Section 3.6.4, we observed for surface cracks and pores. Furthermore, the stereomicroscope was used in observing for internal cracks and pores.

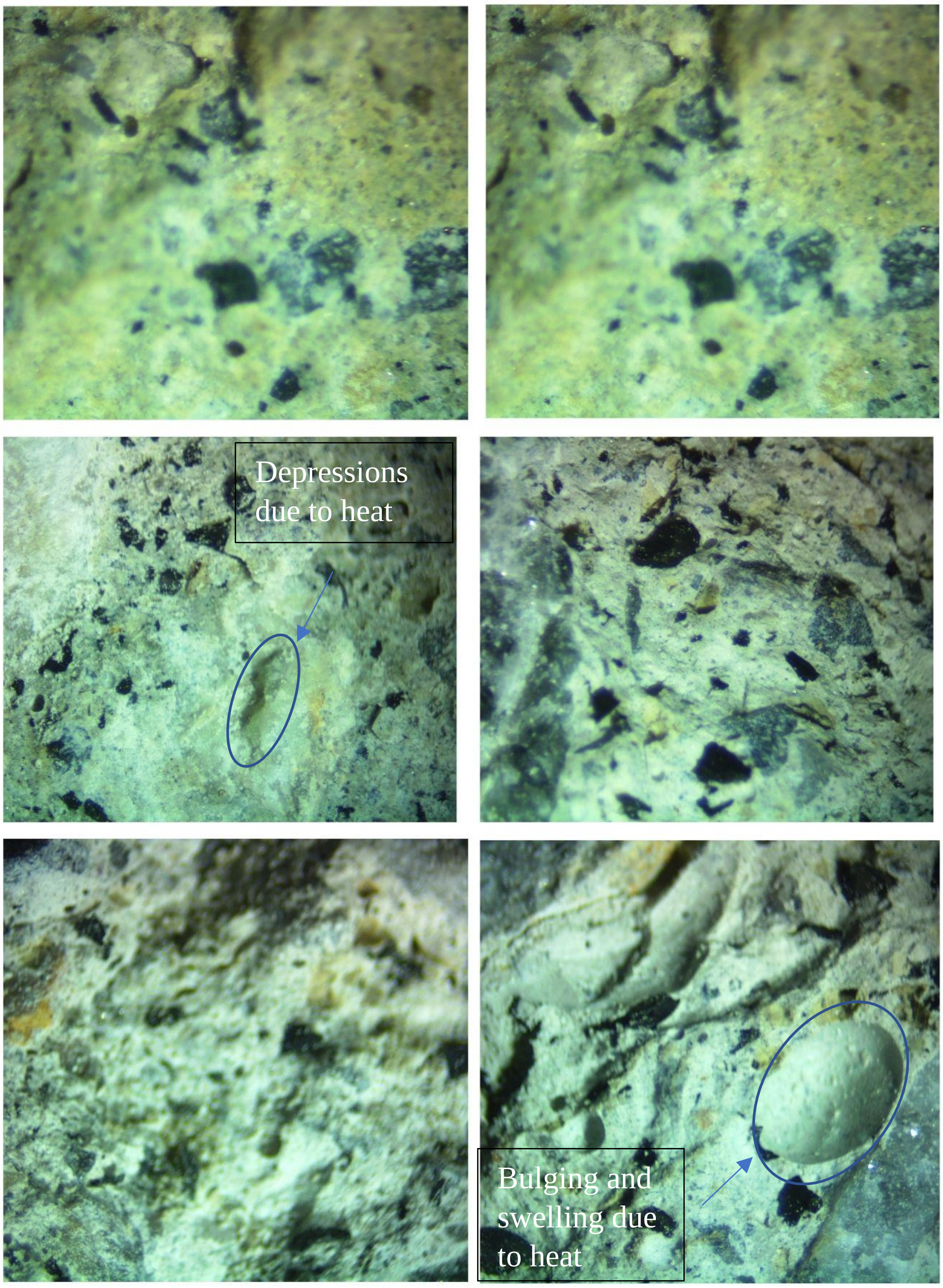
The figures 4.22-4.26 below are a grid of stereomicroscope images after exposure to temperatures. In these images you will notice the crystalline look of control concrete (Figure 4.22). This is owing to due to C-S-H gel, and other hydration compounds. This is less in CRC due to the increased volume of constituents using up the binder paste. As crumb rubber content increases, the reduced binder causes stronger permeation by heat. In Figure 4.25 – 4.26, this permeation is pronounced by heat marks, shown with red ink. Another feature that is common, particularly from Figure 4.25 – 4.26 is the elongation, and enlargement of rubber aggregates due to heat. This enhances the ability of Crumb Rubber Concrete (CRC) to absorb heat, and depict less conduction and transfer compared to control concrete. This better response to heat than control concrete, is limited to moderate replacement ratios.



Legend

7-days	28-days
Rm. Temp.	Rm. Temp.
100°C	100°C
200°C	200°C

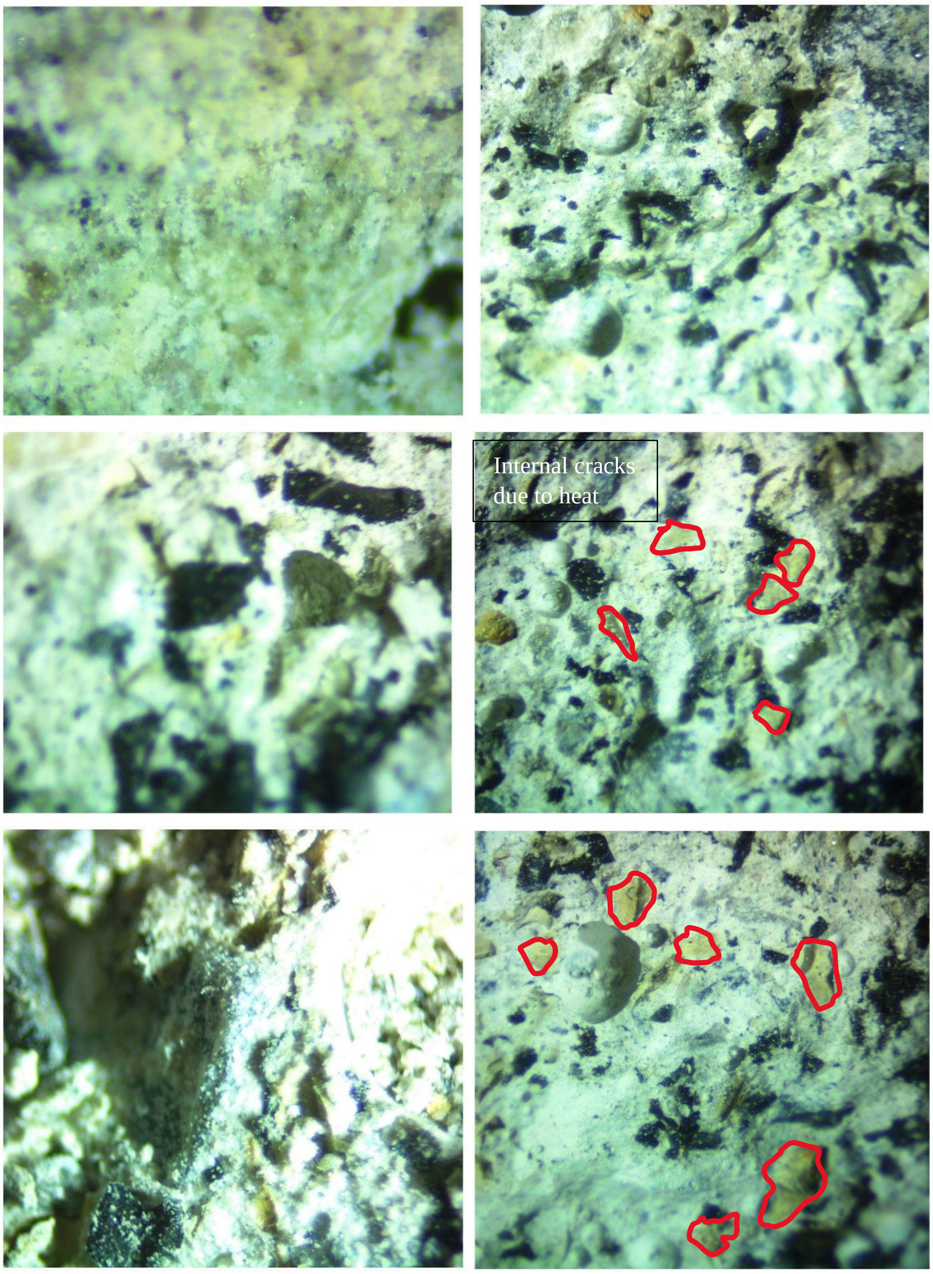
Figure 4.22: Stereomicroscopic view of control concrete



Legend

7-days	28-days
Rm. Temp.	Rm. Temp.
100°C	100°C
200°C	200°C

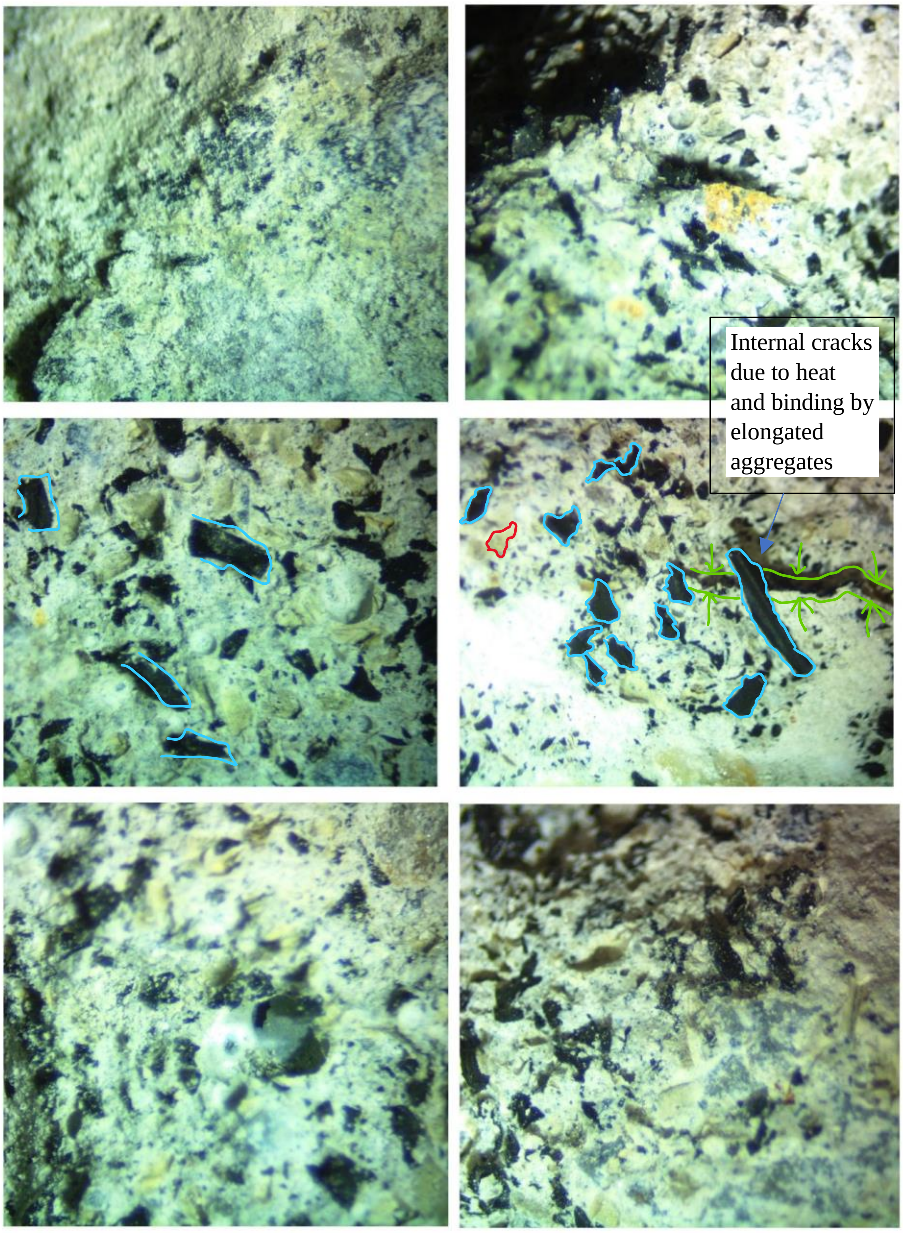
Figure 4.23: Stereomicroscopic view of 10-CR



Legend

7-days	28-days
Rm. Temp.	Rm. Temp.
100°C	100°C
200°C	200°C

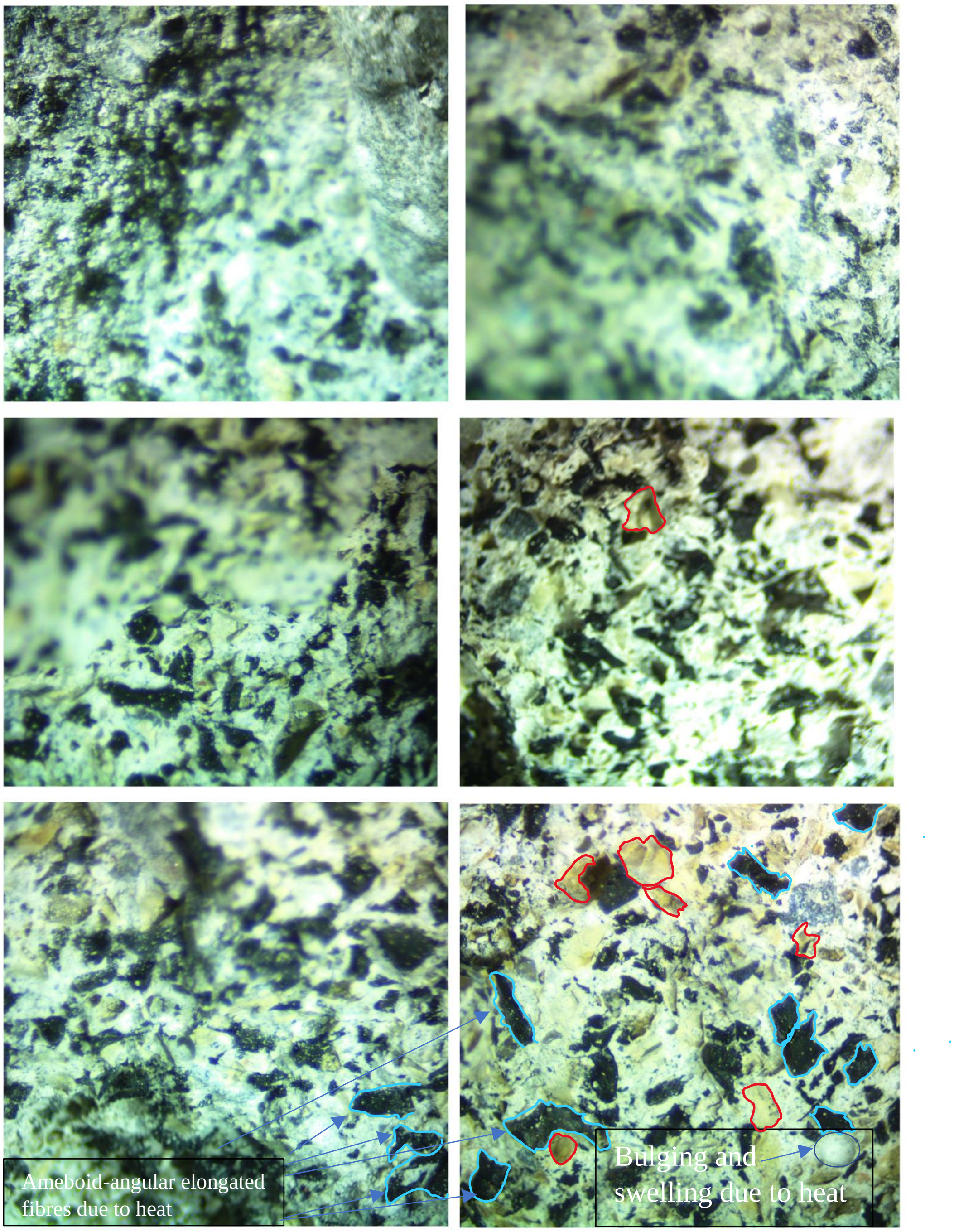
Figure 4.24: Stereomicroscopic view of 20-CR



Legend

7-days	28-days
Rm. Temp.	Rm. Temp.
100°C	100°C
200°C	200°C

Figure 4.25: Stereomicroscopic view of 30-CR



Legend

7-days	28-days
Rm. Temp.	Rm. Temp.
100°C	100°C
200°C	200°C

Figure 4.26: Stereomicroscopic view of 40-CR

In Figure 4.27 – 4.33, for 30-CR, and 40-CR, there were visible surface cracks as a result of exposure to elevated temperatures. However, only 40-CR had surface pores development resulting from heat. In Figure 4.27 -4.33, you will see image of this, and enlarged view of the image area in focus. There were color changes from 20-CR, 30-CR, and 40-CR. Increased permeation in concrete with 20% and above replacement of crumb rubber resulted in generating sufficient heat intensity to produce color changes from natural aggregates in the concrete. This comes about by the iron content commonly found in natural aggregates (Lee, Choi, & Hong, 2010). In figure 4.3.4; length of surface pores and crack width are plotted against concrete type on exposure to 200°C.

Figure 4.27: L-R, 7-day and 28-day surface of 30-CR before heating

Figure 4.28: L-R, 7-day and 28-day surface of 40-CR before heating

Figure 4.29: surface cracks of 30-CR at 7-day age after heating at 200°C


Figure 4.30: surface cracks of 30-CR at 7-day age after heating at 200°C


Figure 4.31: surface cracks of 30-CR at 28-day age after heating at 200°C

Figure 4.32: surface cracks of 40-CR at 7-day age after heating at 200°C

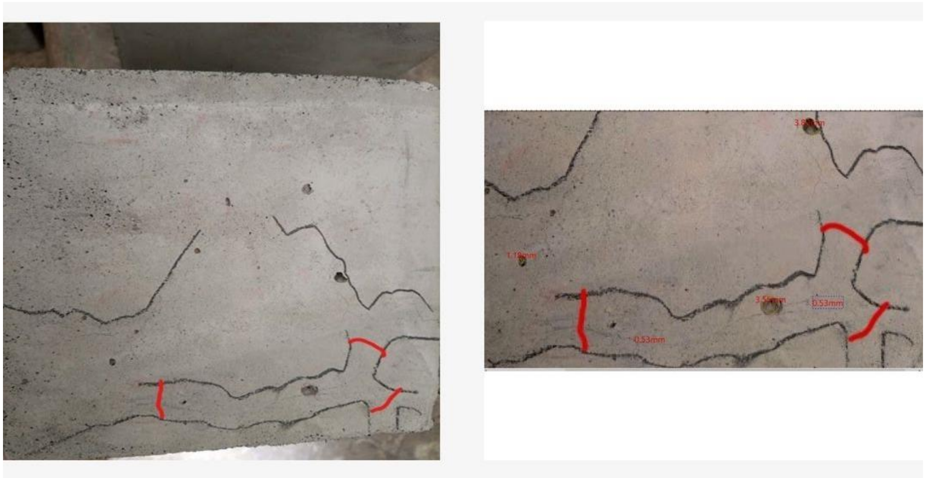


Figure 4.33: surface cracks and pores of 40-CR at 28-day age after heating at 200°C

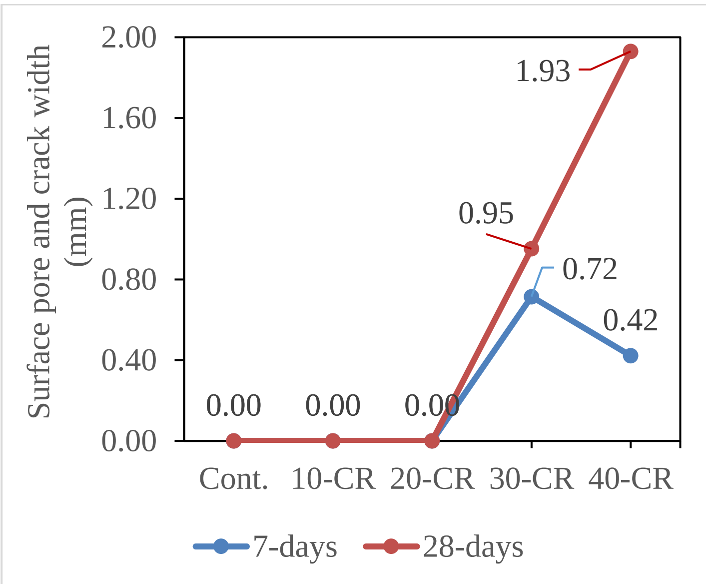


Figure 4.34: surface cracks of CRC exposed to 200°C

4.3.5 Crumb Rubber impressions on permeability

In Fig 4.35 below, permeability increased disproportionately with 10-CR, 20-CR, and 40-CR. In the case of 30-CR, there was a drop. However, this lower value was still higher than control concrete. Permeability in the 30-CR was visual in large areas of the split specimen, as shown in Figure 4.36 but not in the main pressured region. This is responsible for the surprisingly low reading. In cases of replacement by foreign constituents, after the first two mixes out of four or five mixes; it is advisable to use the Rate of Water Absorption as the ultimate guide.

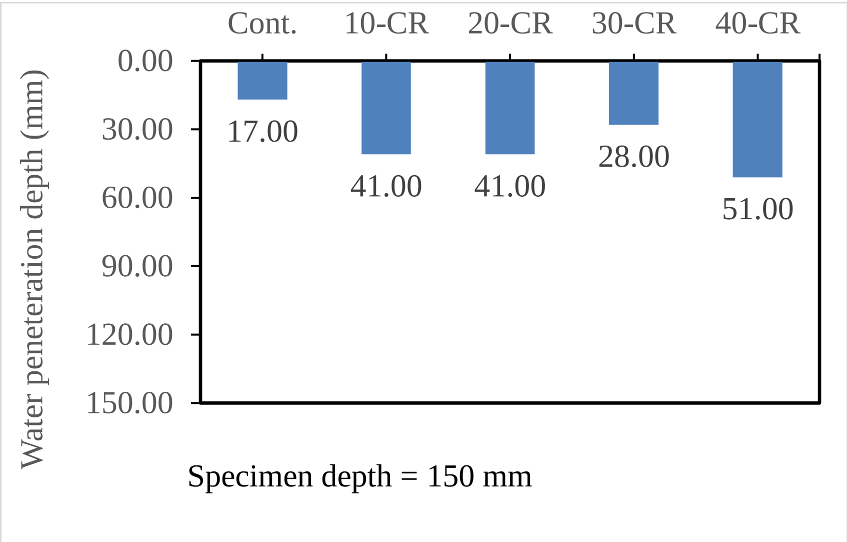


Figure 4.35: CRC permeability at 28 days

Most authors suggest that permeability should be capped at 1/3 – 2/3 of the overall standing height. Beyond this, other tests such as porosity, and diffusivity are more appropriate. Some others have stated that concrete may in fact, show curing moisture still present at lower depth of the standing height after three days. Other issues such as patterns that do not conform to point of applied pressure, add to this invalidity. In Figure 4.36 below (See Appendix C also for others), a 30-CR sample shows sufficient water path but away from the concentration of applied pressure. Other authors say that with increased research in foreign elements introduced into the concrete matrix, there is a good chance that water percolates only to a limited depth before facing tortuous path that causes it to meander away from the concentration of pressure (Villagrán, Sosa, & Di Maio, 2018). Hence this does not mean impermeable concrete altogether.

Permeability is becoming an interesting parameter for quality control of concrete. Some authors say that this characteristic is a specification by itself, and should be considered separately i.e., impermeable concrete is needed in places of hydraulic need. In research carried out in India, they produced M30, M40, and M50 with 0.3, 0.4, and 0.5 w/c ratios; nine mixes in all. It was discovered various combination of results; same permeability with different w/c ratios, same permeability with different compressive strengths, different permeability with same w/c ratios, and different permeability at the same compressive strength. In the end, they agreed that despite seeming mathematical connections, performance-based reasoning drawn from the research left them to conclude that permeability is best treated as a standalone property of concrete. At the closest, compressive strength can impress on permeability; there is not much integrity to hold in the reverse direction (NP-TEL, 2014).

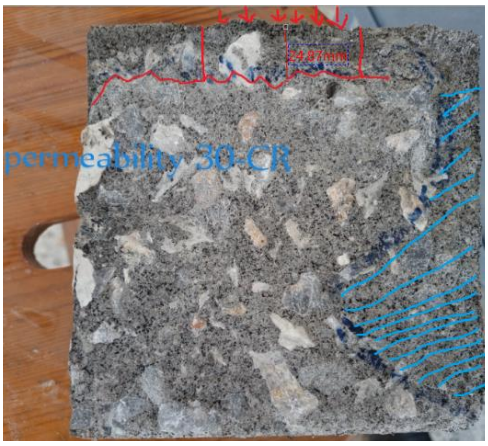


Figure 4.36: Sample permeability view of 30-CR

4.3.6 Crumb rubber ramifications on rate of water absorption

Just as in other studies, Figure 4.37 below showed water absorption to increase with increasing ratios of crumb rubber (Aliabdo, AEM, & MM, 2015; Salehuddin, Rahim, Mohamad Ibrahim, Tajiri, & Zainol Abidin, 2015; Pham, et al., 2019). It has been suggested that for optimal absorption, we should limit the replacement to maximum 15%. At this dosage, difference between oven-dry mass A, and apparent immersed mass B, was minimal. Authors also suggest replacement of cement with ground rubber i.e., <200 microns, impressed in rate of water absorption. The result in Figure 4.36 below closely lines up with Girskas and Nagrockiene (2017). They found increased absorption of 4.95% difference at 20%-CR, compared to difference of 3.5% at 20%-CR w.r.t control concrete, in this reseacrh. The rate of water absorption test reveals some knowledge on the possible voids that can be introduced into concrete. Concrete is typically laced with pores. They play a significant role in concrete. From gel pores containing C-S-H gel as small as 0.005 microns, to capillary pores of common size 0.082 – 0.121 microns through which concrete breathes. Permeable pore spaces shown in Figure 4.35 have been judged in the literature, to be in the size of 0.1 – 1 micron. There is need to study the size and development of these pores by porosimetry, and other methods. These are all the pore spaces within the solid, larger than the gel pores. Figure 4.35 shows that despite increase in volume of permeable voids, 10-CR, and 20-CR are within admissible ranges of conventional normal weight concrete i.e., <16% (CCAA, 2009).

We can obtain information on pore size from the results shown in Figure 4.37 below. Also, the amount of permeable pore spaces, can tell on the presence of macro pores within the matrix. This ultimately informs us of the compaction required by the concrete mix, or its compatibility altogether (Department of Civil Engineering, 2014).

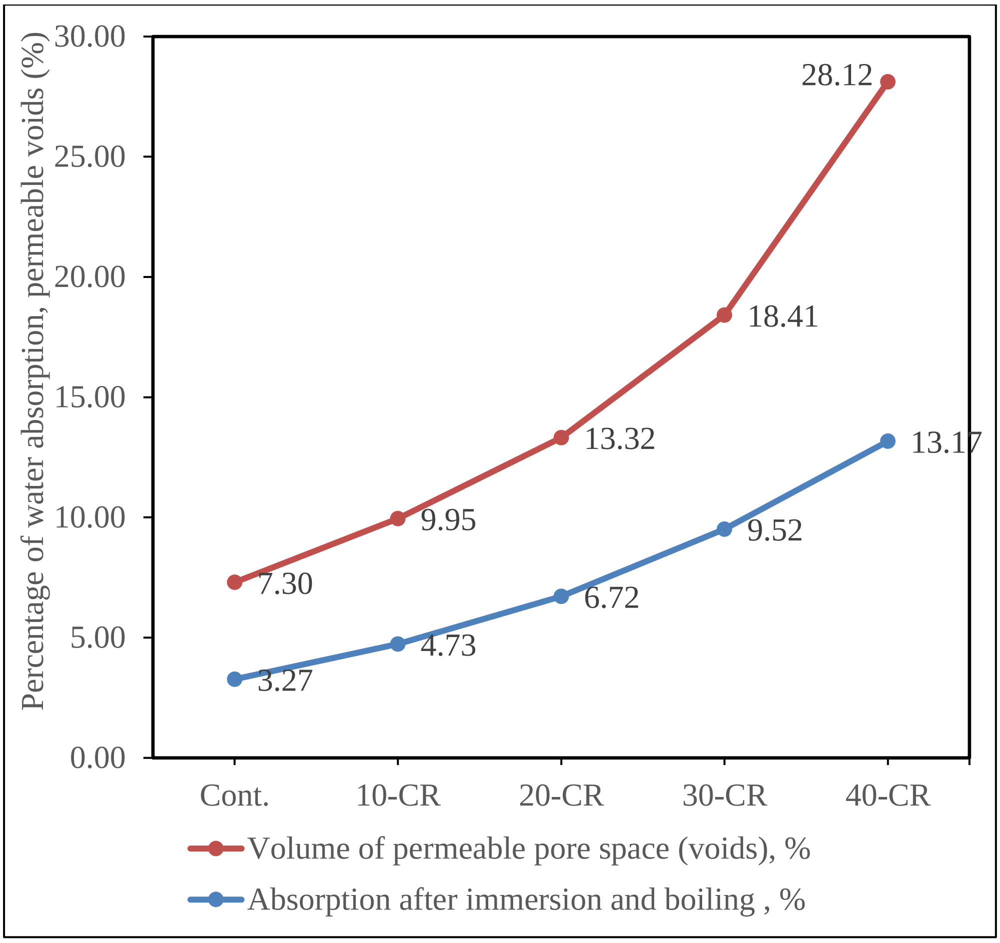


Figure 4.37: Rate of water absorption, of CRC

The Table 4.15 below is a guide that can be used to appreciate the Volume of Permeable Voids (VPV) values.

Table 4.10: Volume of Permeable Voids Chart

Type	Ratios
Water-tight	4.4 – 7.9%
Compact	6.4 – 10.9%
Moderate	9.9 – 13.5%
Permeable	11.4 – 16.4%
Pervious	12.7 – 21.9%

Source: (Paulini, 2019)

In Figure 4.38, a multilinear correlation is plotted amongst percentage increase of air content, percentage increase of voids, and percentage decrease in slump; against crumb rubber content. This plot shows three strong simultaneous linear relationship.

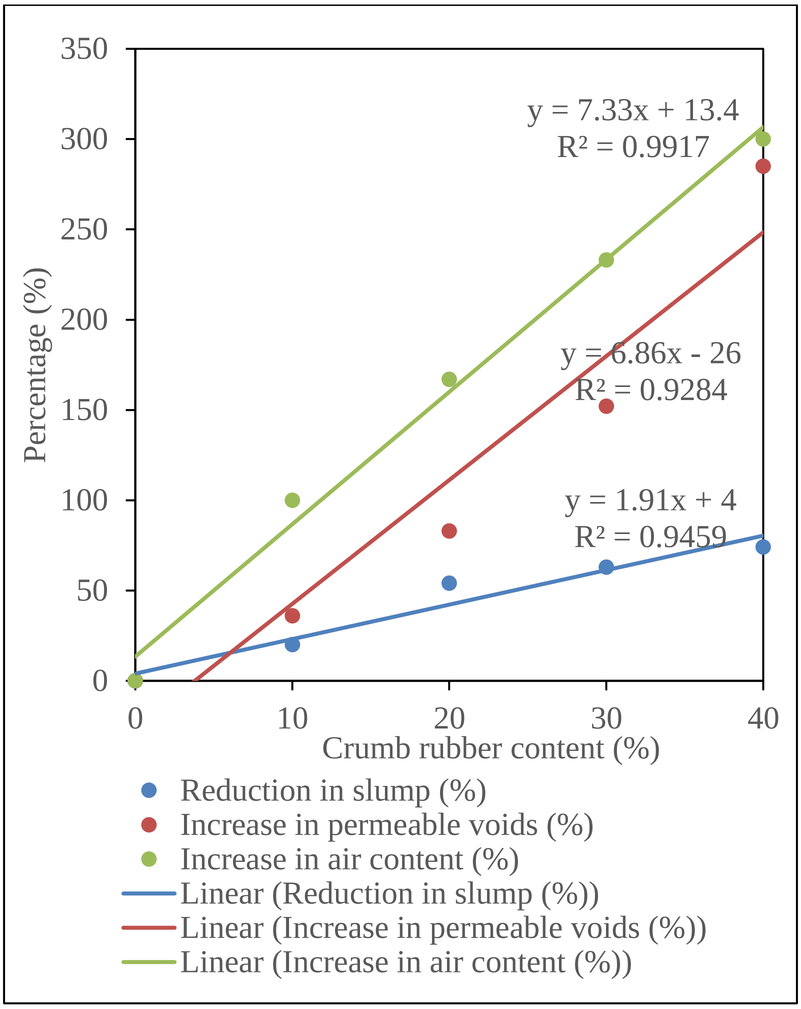


Figure 4.38: Correlation between fresh and durable properties of CRC

4.3.7 Crumb rubber mark on ultrasonic pulse velocity (UPV)

In Figure 4.39 below, UPV decreased minimally with 10-CR, and then steeply with 20-CR, the remaining increase was gradual up till 40-CR. In like manner, Jafari & Toufigh (2017) tested 0, 10, 20, and 30% fine aggregates substituted by crumb rubber with sizes of 4 mm. He found that UPV decreased as replacement ratio increased (Jafari & Toufigh, 2017). Other authors have touted that coarser rubber particles yielded better UPV results. A much higher velocity obtained might be due to less interference in transmission between the knobs, unlike the case of fine rubber, where abundant grade sizes in the matrix will lead to higher interference and increased transmitting time. A strong logarithmic correlation is also plotted between UPV and strength at compression of all samples at 28-day age, in Figure 4.40 below. Al-Qatamin (2019) discovered similar strong linear correlation of 0.986 between UPV and strength at compression for Normal Strength Concrete (NSC) (Al-Qatamin, 2019).

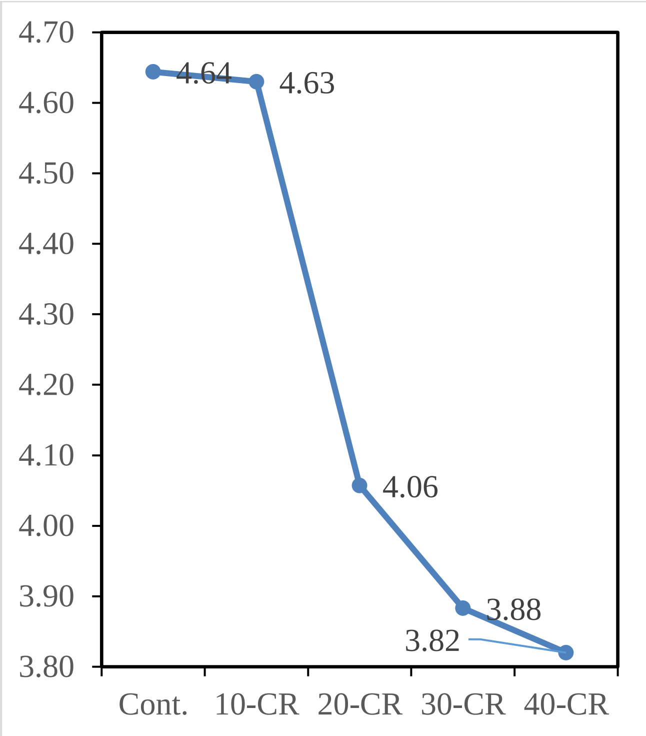


Figure 4.39: Ultrasonic pulse velocity of CRC

Table 4.11: UPV grades

Pulse Velocity (Km/second)	Concrete Quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

Source: (Civil Engineering Portal, 2022)

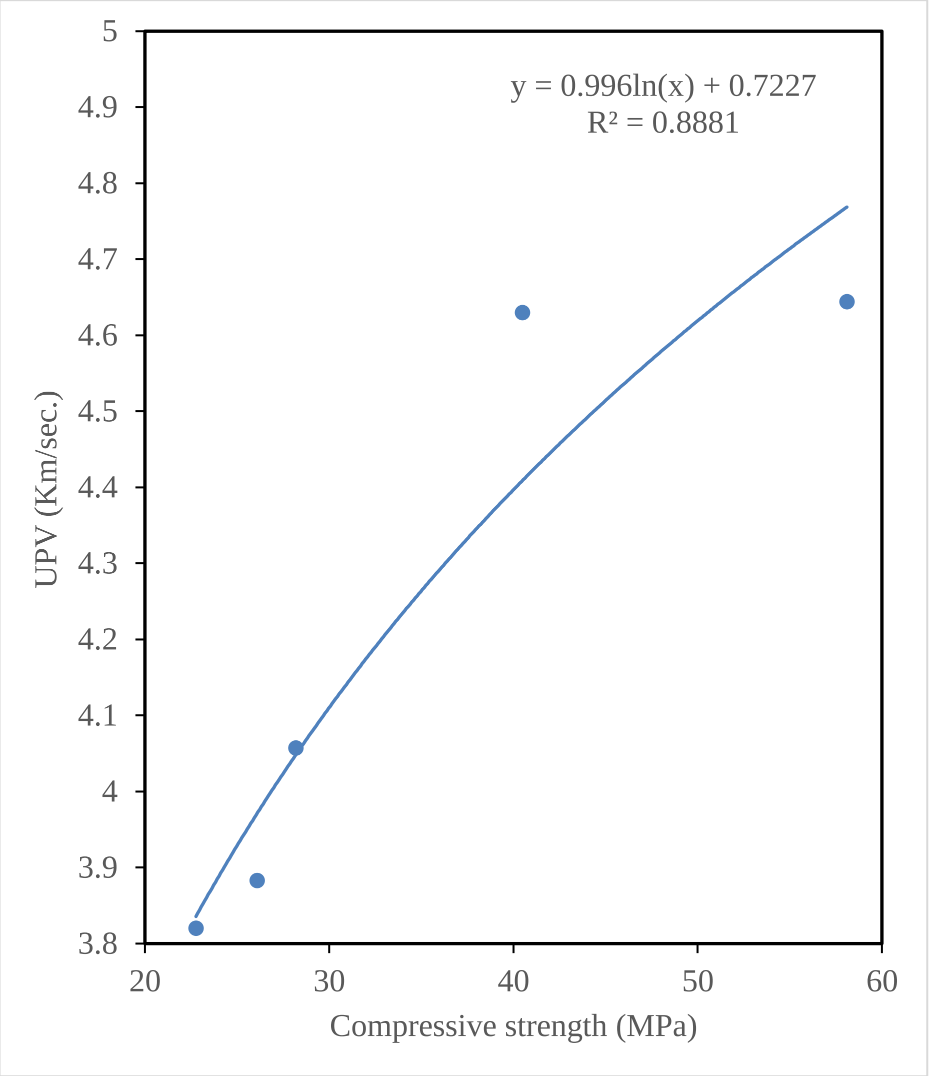


Figure 4.40: Connection between ultrasonic pulse velocity of CRC and compressive strength

4.4 Cost analysis

In Table 4.12 next, cost consequence of assembling a plant for tyre recycling rubber granule line is done. This outfit is estimated to recycle 500-600 Kg/hr. of waste tyre rubber, with an output <4.25 mm.

Table 4.12: Cost analysis of crumb rubber production in North Cyprus

Equipment / Service	Power rating (KW)	Rate / costs	Costs
Sidewall cutter	2.20		
Strips cutter	4.00		
Blocks cutter	15.00		
Tire debeader	15.75		
Rubber breaker	45.00		
Main Screen	7.50		
Main conveyor	1.50		
Mixing conveyor	0.75		
Magnetic separation conveyor	0.75		
Finished screen	2.20		
Finished product conveyor	shared with the finished screen		
Electric control cabinet	Centralized control of equipment		
Miscellaneous	30.00		
Total energy	124.65	124.65 x 20 working days @ 8H per working day = 19,944KWH per month	19,944 @ 4 TL* tariff = 79,776 TL per month
Equipment / Service	Rate / costs	Costs	
Cost of tyre rubber recycling granule line	42,460 USD	42,460 USD	
Cost of installation labour	2,500 USD	2,500 USD	
Used 10-tire Tipper	15,000 USD	15,000 USD	
Fuel	200 litres of diesel per month @ 20 TL per liter	4,000 TL per month	
Manpower	10 personnel @ 7,000 TL per month	70,000 TL per month	
Building space i.e., banking, store	243 sq. m with compound space totaling up to 1100 sq. m	2,300 TL per month	

*1 TL = 0.055 USD

Table 4.13: Cost comparisons of 1 m^3 of control concrete, and Crumb Rubber Concrete in North Cyprus

Volume of concrete	1 m^3 of fine aggregates for control concrete	1 m^3 of control concrete	1 m^3 of fine aggregates for crumb rubber concrete		1 m^3 of 10-CR
Weight of material	578.90 Kg of fine crushed rock @ 250 TL per MT	1616 TL per m3 of concrete	521.01 Kg of fine crushed rock @ 250 TL per MT	57.89 Kg of crumb rubber @ 2000 TL per MT	1616 - 145 +130 + 116 TL
Costs	145 TL	1616 TL	130 TL	116 TL	1717 TL
Total costs	145 TL	1616 TL	246 TL		1717 TL

*1 TL = 0.055 USD

Although, 10-CR is nearly 70% costlier than control concrete when comparing the fine crushed aggregates alone, and about 6.30% more when comparing both concrete, assuming dry weights. This is a positive direction that aligns with SDG 12.7 and 12.8, Promote sustainable procurement practices, and universal understanding of sustainable lifestyles; and 15.A, increase financial resources to conserve and sustainably use ecosystem and biodiversity. Furthermore, investments in recycling will lower the costs of crumb rubber.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this experimental study, 10-CR was discovered to be the best of all CRC tested. It performed above others, on most fresh and hardened properties alike.

1. On workability, 10-CR was the best option. It had least reduction of 20% on slump, and one (1) second more, on vebe time.
2. On air content, it increased steadily from 0.6% for control concrete to 2.4% for 40-CR.
3. Unit weight reduced steadily from about 2360 Kg/m^3 for control concrete, to about 1945 Kg/m^3 for 40-CR.
4. On compressive strength, there was not so uniform depreciation from 58.1 MPa for control concrete at 28-days, to 22.7 MPa for 40-CR at 28-days. Percent reductions were slightly lesser at 7-days when the reduced hydration compounds present in CRC are still active. 10-CR recorded a 28-day compressive strength of 40.5 MPa. This 30% loss is common with values arising from the literature.
5. Similar to compressive strength, split-tensile strength kept up similar percent reductions. It is sterling to note that the percentage reduction did not increase steadily with age according to compressive strength. This can be attributed to the improved performance that Crumb Rubber Concrete (CRC) depicts on

exposure to tensile loads at mature ages. The toughened crumb rubber produces a non-brittle resistance to such loads resulting in a consistent percentage gap with control concrete from seven (7) days at 24 – 55% loss, to twenty-eight (28) days at 32 – 59%.

6. Flexural strength results resembled split-tensile strength results with same kind of behavior to loads. This comes about by improved performance that is depicted by Crumb Rubber Concrete (CRC) on exposure to tensile loads at mature ages. The percentage decreases w.r.t. control concrete was tighter in consistency than the former; losses accounted at seven (7) day age were 24 – 55%, for 10-CR to 40-CR; and for twenty-eight (28) days, they were at 32 – 59%, for 10-CR to 40-CR.
7. When tested for split-tensile strength after degradation at 100°C, and 200°C; there was better performance from specimens exposed to 200°C at 7-days. However, at mature ages, there was relative parity in performance between specimen exposed to 100°C, and 200°C.
8. Permeability increased from 20.75 mm for control concrete; by 23.92 mm for 10-CR, 24.49 mm for 20-CR, 11.91 mm for 30-CR, and to a maximum for 40-CR.
9. Volume of Permeable Voids (VPV) %, increased by a difference of 2.65% for 10-CR, 6.024% for 20-CR, 11.114% for 30-CR, and 20.819% for 40-CR. Absorption after immersion and boiling (%) was 3.271% for control concrete; afterwards, there was 45% increase for 10-CR, and 42% increase between interval from 10-CR to 20-CR, and from 20-CR to 30-CR, and a 38.32% from 30-CR to 40-CR.

10. UPV of control concrete was 4.644 Km/sec, 4.63 Km/sec for 10-CR, 4.057 Km/sec for 20-CR, 3.883 Km/sec for 30-CR, and 3.82 Km/sec for 40-CR.
11. Costing has been carried out for setting up crumb rubber outfit, and comparing a cubic meter of control concrete and 10-CR. It revealed that a crumb rubber factory significantly rivals cost of stone mining facility. Moreover, single equipment for stone mining can cost in excess of 50,000 USD. Crumb rubber production is significantly independent of political strings, when compared to stone mining by blasting rock, or dredging river sand. Finally, cost per cubic meter of fine aggregates for one cubic meter of control and 10-CR was analyzed, as well as the cost of the mixed concrete, assuming dry weight. The research has shown that, despite obvious cost increase per cubic meter of fine aggregates, and reasonable cost increase per cubic meter of concrete; it aligns with SDG targets as explained; encouraged investments in sustainable practice will promote financial competitiveness of crumb rubber in the aggregates market.

Despite these reductions, Crumb Rubber Concrete (CRC) showed when subject to tensile and flexural load, an unusual kind of durability compared to conventional concrete, owing to its non-brittle nature. Interestingly, CRC showed better response to heat degradation in some instance particularly 10-CR – 30-CR i.e., relatively low thermal conductivity.

5.2 Recommendations

There is further promise of CRC as a viable option for application in some highway instruments such as guard rail in bridges; and others like barrier concrete, defense carry-ons, and interlocking pavement. It is also touted that CRC will serve better when used in pile caps of bridges, and sleepers of railways (Hameed & Shashikala, 2016). To thoroughly ascertain this, CRC should be tested for impact energy. There is little research on warm properties of CRC, as mentioned in the introductory chapter. Related tests like thermal conductivity should be carried out on CRC. Other upcoming aspects of CRC, are its ability to transmit sensory information within the concrete matrix. Thus, it may have potential for repair, retrofitting, and self-healing. It should be mentioned that the putrefiable nature of Waste Tyre Rubber (WTR) will prove effective in fighting organisms that attack concrete in such aggressive environment.

To drastically improve the performances of CRC, particularly in its strength and durability properties; it has been advised to treat crumb rubber by soaking in conc. NaOH according to practice in the literature before applying to concrete. They discovered that the improved adhesion with cement paste will enhance strength, and durability properties. Inclusion of chemical admixture to improve properties, particularly strength and flowability is likely. There is need to exercise caution on the overall environmental impact of this substance applied to concrete (kao, 2022).

Another way to enhance CRC performance will be to apply ‘particular’ grade replacement within the strata of the fine aggregate, rather than replacing entire portions by mass or weight. An illustration is given in Figure 5.1 below.

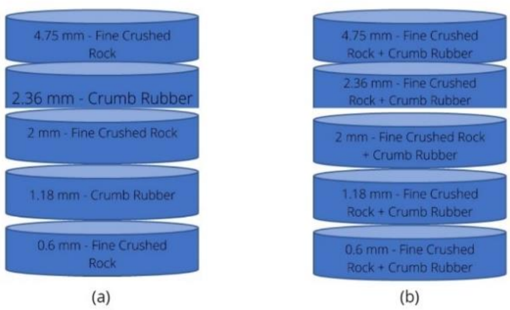


Figure 5.1: (a) grade-specific replacement (b) generic replacement

It is widely believed from existing research that grade-specific replacement depicted in Figure 5.1 (a), as compared to (b), will unify the fine aggregate and make it more potent within the concrete matrix. This better-homogenized fine aggregates will produce concrete greater in elastic moduli, and abrasion resistance, with much more dimensional stability.

Further research can be done in areas pertaining to fracture, toughness, abrasion resistance, energy-dissipating capacity, fatigue, ductility, soundness, and damping ratio. These areas are touted as CRC strongholds over conventional concrete. In addition, the elastic properties of crumb rubber, and how this impacts its load-deformation behavior. This future research can be supported by treatment of crumb rubber, which has shown promise in the past, namely, NaOH-treated crumb rubber, and cement-treated crumb rubber. Understanding these properties can improve the chances of crumb rubber in;

i). High Performance Concrete (HPC) applications,

ii). flexure performance,

iii). solving dynamic problems in multi-frame structures,

iv). cyclic loading,

v). deflection,

vi). withstanding weathering, and

vii). Freeze-thaw conditions.

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APPENDICES

Appendix A: Control concrete mix design

Concrete mix design form — Job title: MS Thesis mix design

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	45 N/mm² at 28 days; Proportion defective 5 %
	1.2 Standard deviation	Fig 3	8 N/mm² or no data / N/mm²
	1.3 Margin	C1 or Specified	(k = 1.64) 1.64 × 8 = 13.12 N/mm²; / N/mm²
	1.4 Target mean strength	C2	45 + 13 = 58 N/mm²
	1.5 Cement strength class	Specified	42.5
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed Crushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.405 } Use the lower value: 0.405
	1.8 Maximum free-water/cement ratio	Specified	
2	2.1 Slump or Vebe time	Specified	Slump >100 mm or Vebe time 1-3 s
	2.2 Maximum aggregate size	Specified	>100 mm
	2.3 Free-water content	Table 3	237.5; 237.5 kg/m³
3	3.1 Cement content	C3	237.5 ÷ 0.405 = 586.4 kg/m³
	3.2 Maximum cement content	Specified	580 kg/m³
	3.3 Minimum cement content	Specified	kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1: 580 kg/m³
	3.4 Modified free-water/cement ratio		0.409
4	4.1 Relative density of aggregate (SSD)		2.74 known/assumed
	4.2 Concrete density	Fig 5	2382 kg/m³
	4.3 Total aggregate content	C4	2382 − 580 − 237.5 = 1564.5 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	54 %
	5.2 Proportion of fine aggregate	Fig 6	37 %
	5.3 Fine aggregate content	C5	0.37 × 1564.5 = 578.9 kg/m³
	5.4 Coarse aggregate content	C5	1562 − 578.9 = 985.6 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	580	235	580	490	495	
per trial mix of 0.030 m³	17.4	7.13	17.37	14.78	14.78	

[illegible]

Appendix B: Sample permeability views

Hardened concrete

Control concrete

Compressive strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	34.9	39.9	39.0	31-03-2022
Maximum Load (KN)	786	898	878	
Dry Density (Kg)	8.210	8.200	8.430	

Compressive strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	58.4	57.6	58.3	22-04-2022
Maximum Load (KN)	1314	1296	1312	
Dry Density (Kg)	8.100	7.840	7.960	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	3.406	3.426	3.410	06-04-2022
Maximum Load (KN)	120.4	121.1	120.5	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	5.254	5.237	5.190	22-04-2022
Maximum Load (KN)	186	185	183	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	5.634	5.620	5.618	19-04-2022
Maximum Load (KN)	11.3	11.2	11.2	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	28-days

Strength (MPa)	6.211	6.115	6.009	10-05-2022
Maximum Load (KN)	12.4	12.2	12.0	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.746	1.750	1.772	07-04-2022
Maximum Load (KN)	61.7	61.9	62.6	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.810	2.717	2.918	17-05-2022
Maximum Load (KN)	99.3	96.0	103.1	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.797	1.809	1.812	07-04-2022
Maximum Load (KN)	63.5	63.9	64.0	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.011	2.055	2.066	17-05-2022
Maximum Load (KN)	71.1	72.6	73.0	

Permeability	Specimen 1a	Specimen 1b	Specimen 2a	28-days
Water penetration depth (mm)	16.50	17.50	25.20	25-04-2022
	Specimen 2b			
	23.80			

Rate of Water Absorption	Specimen 1	Specimen 2	Specimen 3	28-days
A (g)	7775	7610	7979	28-04-2022
B (g)	8105	7990	8325	
C (g)	8008	7894	8225	
D (g)	4534	4470	4657	

UPV	Specimen 1	Specimen 2	Specimen 3	28-days
pulse velocity (mm/microsec.)	32.1	32.4	32.4	22-04-2022

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Compressive strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	33.1	34.6	28.8	31-03-2022
Maximum Load (KN)	748	779	648	
Dry Density (Kg)	7.710	8.170	7.910	

Compressive strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	38.6	41.8	41.2	17-05-2022
Maximum Load (KN)	869	941	927	
Dry Density (Kg)	7.815	7.690	7.740	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	2.714	2.613	2.546	26-04-2022
Maximum Load (KN)	95.9	92.4	90.0	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	3.595	3.555	3.579	17-05-2022
Maximum Load (KN)	127.0	125.6	126.5	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	4.577	3.939	3.947	26-04-2022
Maximum Load (KN)	9.2	7.9	7.9	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	4.231	4.638	4.595	10-05-2022
Maximum Load (KN)	8.5	9.3	9.2	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.290	1.300	1.431	18-05-2022
Maximum Load (KN)	45.6	45.9	50.6	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.170	2.188	2.209	17-05-2022
Maximum Load (KN)	76.7	77.3	78.07	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.900	1.911	1.988	18-05-2022
Maximum Load (KN)	67.2	67.5	70.3	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.158	2.146	2.140	17-05-2022
Maximum Load (KN)	76.3	75.8	75.6	

Permeability	Specimen 1a	Specimen 1b	Specimen 2a	28-days
Water penetration depth (mm)	41.00	42.00	43.00	20-05-2022
	Specimen 2b	Specimen 3a	Specimen 3b	
	45.00	48.00	50.00	

Rate of Water Absorption	Specimen 1	Specimen 2	Specimen 3	28-days
A (g)	7545	7315	7325	20-06-2022
B (g)	7820	7595	7590	
C (g)	7898	7671	7666	
D (g)	4264	4210	4207	

UPV	Specimen 1	Specimen 2	Specimen 3	28-days
pulse velocity (mm/microsec.)	32.2	33.1	31.9	22-04-2022

20-CR

Compressive strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	21.2	21.5	16.1	31-03-2022
Maximum Load (KN)	477	484	362	
Dry Density (Kg)	7.370	7.790	7.400	

Compressive strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	28.1	26.9	29.5	20-05-2022
Maximum Load (KN)	632	605	664	
Dry Density (Kg)	7.235	7.000	7.390	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	2.025	2.018	2.014	29-04-2022

Maximum Load (KN)	71.6	71.3	71.2	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.570	2.587	2.598	20-05-2022
Maximum Load (KN)	90.8	91.4	91.8	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	2.988	3.239	3.163	29-04-2022
Maximum Load (KN)	6.0	6.5	6.3	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	3.941	3.690	3.939	20-05-2022
Maximum Load (KN)	7.9	7.4	7.9	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.107	1.106	1.126	29-04-2022
Maximum Load (KN)	39.1	39.1	39.8	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	1.519	1.411	1.309	20-05-2022
Maximum Load (KN)	53.7	49.9	46.3	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.590	1.599	1.617	29-04-2022

Maximum Load (KN)	56.2	56.5	57.1	

Split-tensile strength after 200°C	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	1.261	1.361	1.473	20-05-2022
Maximum Load (KN)	44.6	48.1	52.1	

Permeability	Specimen 1a	Specimen 1b	Specimen 2a	28-days
Water penetration depth (mm)	49.00	49.98	44.27	23-05-2022
	Specimen 2b	Specimen 3a	Specimen 3b	
Water penetration depth (mm)	44.81	41.05	43.95	

Rate of Water Absorption	Specimen 1	Specimen 2	Specimen 3	28-days
A (g)	6960	7140	7005	21-06-2022
B (g)	7220	7385	7240	
C (g)	7459	7607	7457	
D (g)	3934	4012	3933	

UPV	Specimen 1	Specimen 2	Specimen 3	28-days
pulse velocity (mm/microsec.)	35.5	38.5	36.9	20-05-2022

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Compressive strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	18.3	20.5	22.0	31-03-2022
Maximum Load (KN)	412	461	495	
Dry Density (Kg)	7.160	6.915	7.150	

Compressive strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	25.5	25.7	27.1	07-06-2022
Maximum Load (KN)	574	578	610	
Dry Density (Kg)	7.490	7.360	7.550	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.678	1.655	1.650	17-05-2022
Maximum Load (KN)	59.3	58.5	58.3	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.945	2.915	2.927	07-06-2022
Maximum Load (KN)	104.1	103.0	103.4	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	2.948	3..138	2.725	17-05-2022
Maximum Load (KN)	5.9	6.3	5.5	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	3.486	3.490	3.489	07-06-2022
Maximum Load (KN)	7.0	7.0	7.0	

Split-tensile strength after 100°C	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.130	1.103	1.449	17-05-2022
Maximum Load (KN)	39.9	39.0	51.2	

Split-tensile strength after 100°C	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	1.347	1.477	1.277	07-06-2022
Maximum Load (KN)	47.6	52.2	45.1	

Split-tensile strength after 200°C	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.321	1.311	1.393	07-05-2022
Maximum Load (KN)	46.7	46.3	49.2	

Split-tensile strength after 200°C	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	1.580	1.684	1.497	07-06-2022
Maximum Load (KN)	47.6	59.5	52.9	

Permeability	Specimen 1a	Specimen 1b	Specimen 2a	28-days
Water penetration depth (mm)	28.00	28.60	32.40	10-06-2022
	Specimen 2b	Specimen 3a	Specimen 3b	
Water penetration depth (mm)	32.92	32.00	32.20	

Rate of Water Absorption	Specimen 1	Specimen 2	Specimen 3	28-days
A (g)	6860	7000	6920	22-06-2022
B (g)	7090	7230	7150	
C (g)	7515	7664	7579	
D (g)	3968	4046	4002	

UPV	Specimen 1	Specimen 2	Specimen 3	28-days

pulse velocity (mm/microsec.)	38.5	38.7	38.7	07-06-2022

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Compressive strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	13.1	16.3	16.7	31-03-2022
Maximum Load (KN)	295	367	376	
Dry Density (Kg)	6.960	7.170	7.170	

Compressive strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	23.6	22.6	22.1	10-06-2022
Maximum Load (KN)	531	509	497	
Dry Density (Kg)	7.365	7.185	7.360	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.547	1.527	1.522	20-05-2022
Maximum Load (KN)	54.7	54.0	53.8	

Split-tensile strength	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	2.149	2.130	2.144	10-06-2022
Maximum Load (KN)	76.0	75.3	75.8	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	3.049	2.636	2.864	20-05-2022
Maximum Load (KN)	6.1	5.3	5.7	

Flexural strength	Specimen 1	Specimen 2	Specimen 3	28-days

Strength (MPa)	3.016	3.175	3.163	10-06-2022
Maximum Load (KN)	6.0	6.4	6.3	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	1.336	1.432	1.534	20-05-2022
Maximum Load (KN)	47.2	50.6	54.2	

Split-tensile strength after 100℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	0.008	0.007	0.006	10-06-2022
Maximum Load (KN)	0.3	0.2	0.2	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	7-days
Strength (MPa)	0.839	0.715	0.639	20-05-2022
Maximum Load (KN)	29.7	25.3	22.6	

Split-tensile strength after 200℃	Specimen 1	Specimen 2	Specimen 3	28-days
Strength (MPa)	0.008	0.007	0.006	10-06-2022
Maximum Load (KN)	0.3	0.2	0.2	

Permeability	Specimen 1	Specimen 2	Specimen 3	28-days
Water penetration depth (mm)	51.45	52.35	51.04	13-06-2022
	Specimen 4	Specimen 5	Specimen 6	

Water penetration depth (mm)	51.00	51.18	51.00

Rate of Water Absorption	Specimen 1	Specimen 2	Specimen 3	28-days
A (g)	6775	6845	6860	23-06-2022
B (g)	7090	7185	7185	
C (g)	7657	7760	7760	
D (g)	4488	4549	4549	

UPV	Specimen 1	Specimen 2	Specimen 3	28-days
pulse velocity (mm/microsec.)	38.7	39.5	39.6	10-06-2022

Fresh concrete 24/03 - 25/05

Specimen	Slump (mm)	Vebe (s)	Air content (%)	Unit weight (Kg per cubic metre)
Cont.	175.00	1.40	0.60	2361.25
10-CR	140.00	3.00	1.20	2279.38
20-CR	80.00	5.25	1.60	2177.50
30-CR	65.00	11.00	2.00	2088.75
40-CR	45.00	17.00	2.40	1943.63

Specimen	First drop of Vee Bee rod (mm)	Vee Bee slump (mm)	volume of water (per cubic centimeter) needed to pass through chamber
Cont.	45.00	30.00	13.73
10-CR	105.00	60.00	86.07
20-CR	75.00	55.00	172.50
30-CR	35.00	15.00	213.03
40-CR	15.00	~	343.99

Appendix C: Sample permeability views