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Production of concrete from recycled aggregates

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Chapter 1: What is RAC

1.1 *INTRODUCTION*

Construction/demolition waste can be recycled to help provide a clean environment. Infrastructure development contributes to environmental contamination and impacts climate change. Therefore, it is necessary to recycle the waste products from construction and demolition to create “green” concrete. Studies suggest that employing recycled aggregate (RA) from solid waste concrete instead of natural aggregate (NA) in recycled aggregate concrete (RAC) benefits the economy and environment. It could save 10–20% of material costs, reduce greenhouse gas emissions by 65%, and reduce non-renewable energy use by 58%. RA and RAC are being studied more due to environmental concerns and sustainable development. Over 10,000 RAC publications have been published in the past 20 years (Lu, 2024a) .The Technology readiness level for recycled aggregate concrete is “6” meaning that prototype and subsystems have been successfully demonstrated in relevant environments however full-scale operational use is still limited. Aggregates (fine and coarse) generally account for 60–75% of concrete volume. Various approaches have been suggested to enhance the mechanical properties of RCA. Removing old mortar, using different mixing approaches, and adding mineral admixtures are some of these. The lack of technical guidelines, standard test methods, mixed proportioning methods, and standard code specifications hinders the use of RCA in the construction industries (Kumar & Singh, 2023).To obtain good quality concrete using recycled aggregate it is necessary to follow the minimum requirements defined by the respective building standards. Acceptable properties of aggregates are an elemental base for concrete quality; however adequate mix proportions and concrete production methods are highly important in concrete quality too. Recycled aggregates are composed of original aggregates and adhered mortar. The physical properties of recycled aggregates depend on both adhered mortar quality and the amount of adhered mortar. The adhered mortar is a porous material; its porosity depends upon the w/c ratio of the recycled concrete employed. When structures made of concrete are demolished or renovated, concrete recycling is an increasingly common method of utilizing the rubble. Concrete was once routinely trucked to landfills for disposal, but recycling has several pros that have made it a more attractive option in this age of greater environmental awareness and the desire to keep construction costs down. Its use might substantially increase in the future because of two reasons. Firstly, the sources of rock that can be crushed are likely to decrease, and tax is levied on all newly quarried rock. Secondly, there is a shortage of disposal sites for demolition materials including old concrete and moreover, there is tax on landfill.(Adam M. Neville & J. J. Brooks, 2010)

1.1.1 *HISTORY*

Using material from construction and demolition waste as aggregates to produce RAC (recycled aggregate concrete) in new concrete was firstly introduced and applied during and after the World War II since enormous amount of rubble and debris had been generated after bombardment to cities, especially in United Kingdom and Germany. At that time, it was found that RAC had higher water absorption, lower compressive strength, comparable freeze/thaw resistance, and inferior dry shrinkage compared with NAC.(Wang et al., 2021a)

1.1.2 *General classification*

Recycled concrete is a viable source of aggregate and has been satisfactorily used in granular subbases, soil-cement, and in new concrete. Recycled aggregates are classified in one of two ways, as:

- Recycled Aggregate (RA) - aggregate resulting from the reprocessing of inorganic material previously used in construction.
- Crushed Concrete Aggregate (CCA) – aggregate obtained from crushed concrete.

A specific subset of recycled aggregates is crushed concrete aggregates (CCA) where the content of concrete, concrete products, mortar, concrete masonry units, unbound aggregate, natural stone or hydraulically bound aggregate must not be less than 90%. This high percentage inclusion of 'good' aggregate results in CCA having better performance characteristics than RA and consequently there are fewer restrictions on the use of CCA in concrete. Provision for the use of CCA in concrete is given in BS 8500:2023. (Wang et al., 2021a)

1.2 *Benefits of using R.A.C.*

Recycled aggregate concrete (RAC) offers significant environmental and economic benefits, making it a sustainable alternative to traditional concrete. From a life cycle assessment (LCA) perspective, RAC reduces the demand for natural aggregates, lowers landfill waste, and decreases energy consumption and greenhouse gas emissions associated with raw material extraction and processing. Additionally, life cycle cost (LCC) analyses often show that RAC can be more cost-effective due to savings in material costs and reduced disposal fees. By promoting resource efficiency and minimizing environmental impacts throughout its lifecycle, RAC contributes to a more sustainable construction industry and supports circular economy principles.

1.2.1 *Environmental advantages*

Recycling RCA minimizes landfill construction and demolition waste (CDW) and protects the environment. CDW is often dumped untreated in landfills. The global average is 35% CDW landfilled. Stone Cycling reports that the United States (US) landfilled 24.3% of its CDW, the United Kingdom (UK) 23.6%, and the European Union (EU) 40–60% of CDW either landfilled or backfilled. Landfill rates are less than 3% in the Netherlands and 11.46% in Germany.

Croatia's CDW landfill ratio is 40%, per the World Bank. 98% of China's CDW was landfilled untreated before 2020. These numbers highlight a significant disparity in landfill proportions between developed and developing countries.

Furthermore, CDW constitutes a considerable proportion of total waste in landfills, occupying a substantial amount of landfill space. Evidence indicates that the construction industry generates about 65% of landfill waste in China, 44% in the UK, 44% in Australia, 40~50% in New Zealand (NZ), 40% in Brazil, 29% in the US, 27% in Canada, and 25% in Hong Kong. Accommodating the increasing CDW requires substantial landfill capacity, potentially encroaching on farmland. This shortage of landfill space could lead to heightened environmental concerns and increased waste disposal costs. Additionally, many nations grapple with ecological damage from CDW disposal. Some materials within CDW potentially contaminate soil and groundwater, exacerbating these environmental issues.(Lu et al., 2024).

Approximately 48.3 billion tonnes of NAs were consumed worldwide, and every 5-year growth was estimated as more than 5%.(Wang et al., 2021a)

	Year			% Annual growth	
	2005	2010	2015	2005-2010	2010-2015
North America	3.3	3.0	3.7	-1.7	4.3
Western Europe	2.9	2.6	3.1	-2.1	3.0
Asia/Pacific	16.0	24.8	32.6	9.1	5.7
Other	5.1	7.1	8.9	6.6	5.0
Worldwide	**27.3**	**37.4**	**48.3**	**6.5**	**5.2**

Table 1.Annual growth of the aggregate consumption in billion tonnes.(Wang et al., 2021a)

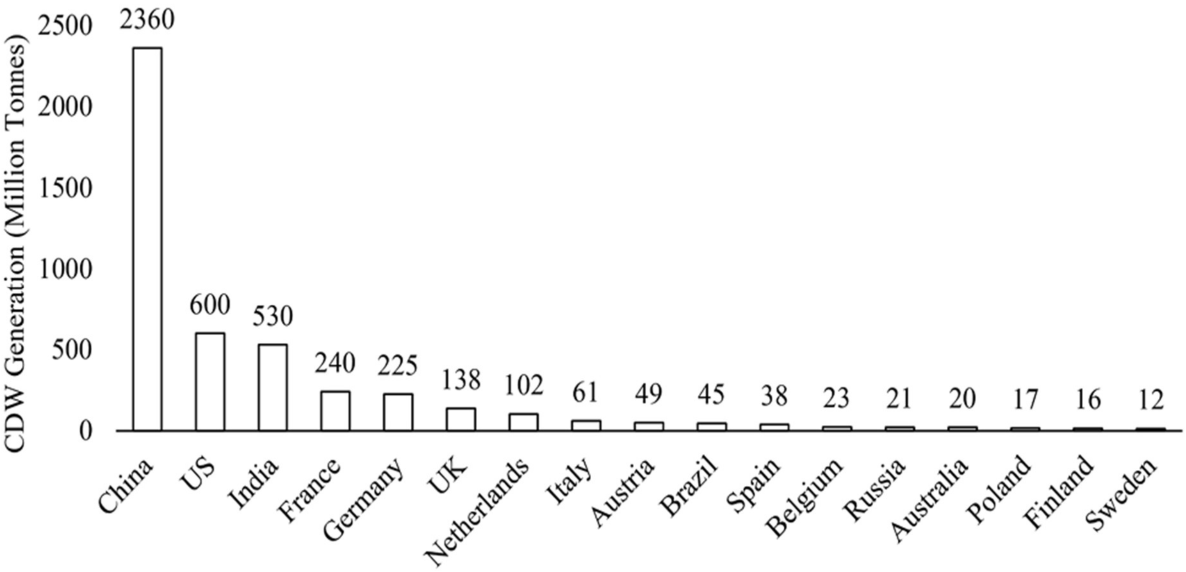


Table 2. Construction and demolition waste of different countries with unit of million tonnes.(Wang et al., 2021)

1.2.2 *CONSERVATION OF NATURAL RESOURCES*

Recycling RCA can significantly reduce the demand for natural aggregates in construction. The past 50 years have seen increased concrete use due to population growth, with aggregates comprising 70–80% of concrete volume.

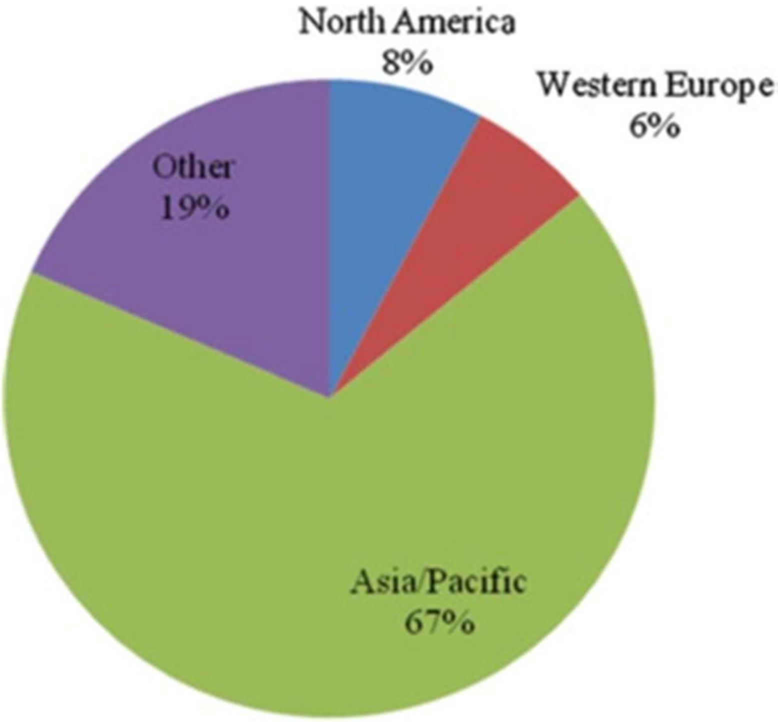


Figure 1. Demand for construction aggregate worldwide(Lu, 2024a)

As indicated in figure 1, Global aggregate consumption peaked at 48.3 billion metric tons in 2015, primarily in Asia and the Pacific, growing annually by 5%. Some countries, like China, now face shortages in quality aggregates, and mining them harms the environment. Thus, RCA, a sustainable alternative, can effectively replace natural aggregates, mitigating environmental impact.(Lu, 2024b; Wang et al., 2021a)

1.2.3 *LOWER CARBON FOOTPRINT*

Lower Carbon Footprint Recycling RCA can significantly reduce the carbon footprint compared to natural aggregates. Natural aggregate production relies on non-renewable fossil energy, contributing to global warming. In Brazil, the carbon footprint for coarse aggregate is 1.50 kg CO2-e per ton, with contributions from extraction, transport, and crushing. Brazil has the ninth largest economy in the world, so this survey's results can represent the carbon footprint of processing natural coarse aggregates in most developing countries. Global carbon emissions from natural coarse aggregate production are astonishing. It is found that producing one ton of natural aggregates emits 0.046 tons of CO2, whereas recycled aggregates emit just 0.0024 tons, reducing emissions by 23–28%. In summary, using recycled aggregates lowers CO2 emissions and mitigates environmental impacts from construction waste.(Lu, 2024b)

1.2.4 *ECONOMIC BENEFITS*

Using recycled aggregates in infrastructure projects offers several economic benefits:

- Lower waste disposal costs: less waste sent to landfills reduces fees, transportation costs, and long-term monitoring expenses.
- Material cost savings: recycled aggregates are typically cheaper than natural aggregates,

leading to significant cost savings in construction.

- ➢ Job creation: the recycling industry expands with increased demand for recycled aggregates, creating more job opportunities. According to (Del Ponte et al., 2017), using recycled materials in road and rail infrastructure can save 2% to 83% in costs, and recycling creates more jobs per 10,000 tons of recovered material than waste disposal. Additionally, USD 62.5 million in savings was predicted from using recycled materials in highway construction. In summary, recycled aggregates reduce costs, create jobs, and support environmental sustainability.(Del Ponte et al., 2017; Lu, 2024b)

1.2.5 *SOCIAL BENEFITS*

The benefits of using recycled aggregates in infrastructure projects extend to the environment, health, economy, and social aspects:

- ➢ Improving welfare by generating jobs: expanding the recycling industry generates new employment opportunities, supporting community welfare and the local economy.
- ➢ Public health: reduced greenhouse gas emissions and pollutants from the use of recycled aggregates improve public health outcomes.
- ➢ Resource conservation: using recycled aggregates preserves natural resources for future generations, promoting intergenerational fairness and stewardship.
- ➢ Civic pride and satisfaction: sustainable building practices enhance community satisfaction and pride in resource management and environmental care.

These advantages collectively contribute to the overall social sustainability of communities.(Lu, 2024b)

1.2.6 *TECHNOLOGICAL BENEFITS*

The use of RCA provides significant technological benefits:

- ➢ Materials development : enhances RCA quality and performance through improved processing techniques, new cementitious materials, and composite effects with other materials.
- ➢ RAC performance assessment : requires novel methods for evaluating mechanical and durability properties, focusing on the interfacial transition zone (ITZ).
- ➢ Construction technology: advances in mix design and admixture studies optimize RAC performance in construction.
- ➢ Structural design: updates to design standards and methodologies to accommodate RAC properties, improving structural design theories.(Lu, 2024b)

To put it in a nutshell, here is a table to point out the importance of the research by mentioning the numerous advantages of RAC.

Factors of Waste Management for Sustainable Construction	Elements
Environmental aspect	1. Reducing environmental pollution 2. Conservation of water, soil, air and noise 3. Reducing the challenges of global warming 4. Reducing barriers to green development 5. Reducing greenhouse gas emissions 6. Reducing fossil fuel emissions 7. Reducing the depletion of resources and raw materials 8. Reducing the effects of illegal dumping, etc.
Economic aspect	1. Reduce material cost 2. Reducing energy consumption 3. Reducing the number of labor and equipment 4. Saving costs associated with transporting waste 5. Saving costs associated with disposal 6. Reducing valuable land-filled costs of damage waiver 7. Reducing costs of reuse and recycling, etc.
Social aspect	1. Reducing the health and safety impacts of waste in the short and long term p 2. Reducing sorting and disposal effort 3. Strengthening the position of project stakeholders towards CDW (construction and demolition waste) management 4. Persuading public opinion and raising awareness towards CDW management 5. Enhancing the role of incentive to prevent illegal dumping 6. Enhancing the aesthetic effects of recycling stored plants and materials, etc.

Table 3.Elements of waste management of sustainable construction.(Makul et al., 2021)

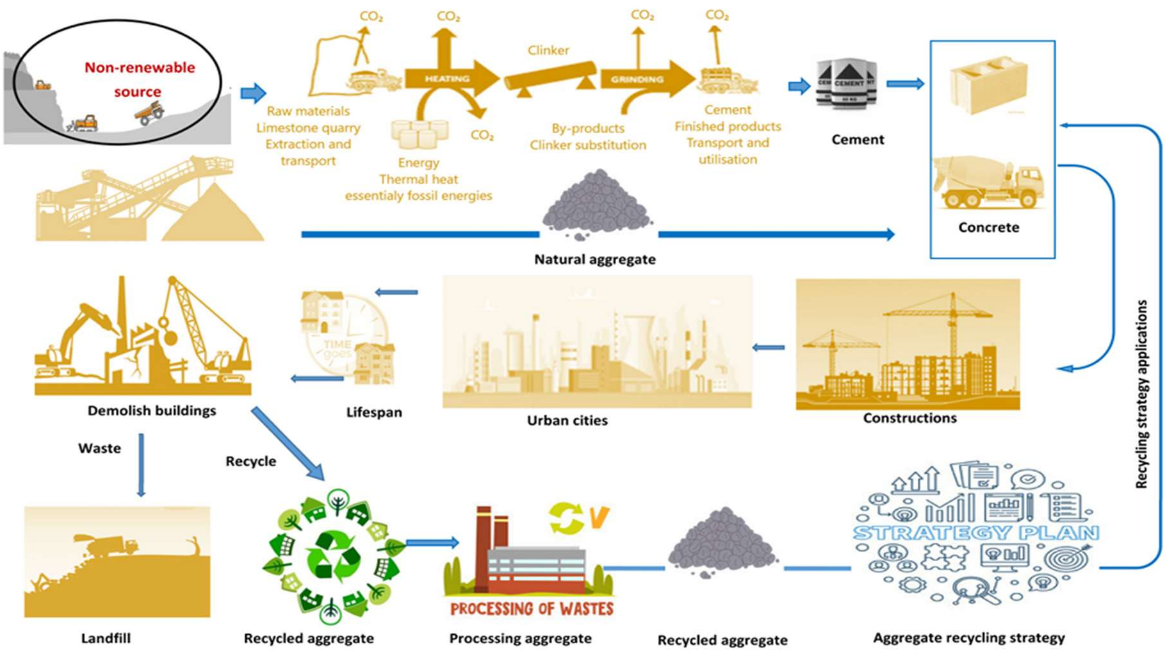


Figure 2. Principles of designing a strategy for recycled aggregate concrete.(Makul et al., 2021)

1.3 ***PRACTICAL APPLICATION OF RAC***

The practical application of recycled aggregate concrete confirms the feasibility of reusing crushed concrete as aggregate in new mixes. In countries such as Japan, high-quality recycled aggregates are routinely incorporated into structural concrete, demonstrating that, with adequate processing, performance comparable to conventional materials can be achieved. Similarly, experimental and demonstration projects in the United Kingdom, such as those developed by the Building Research Establishment (BRE), have successfully utilized recycled aggregates in structural elements. In Netherlands, recycled concrete aggregates are widely applied in pavements, slabs, and infrastructure, particularly in cases where slightly lower or more variable mechanical performance can be tolerated.

In Australia, recycled concrete aggregate (RCA) has been successfully implemented in real construction projects, particularly in road pavement applications where large volumes of material are required, and performance demands are well understood. Municipal and state road authorities have widely adopted RCA as a granular base and sub-base material in pavement structures, replacing traditional quarried aggregates.(Sagoe-Crentsil, 2002)

Figure 3. Parkingway ,driveway and footpath in Kensington,NSW .(Sagoe-Crentsil, 2002)

Figure 4. The walking/bike path of Williamstown,Victoria , using concrete incorporating 100% recycled coarse aggregates. (Sagoe-Crentsil, 2002)

Figure 5. The footpath of Werribee south,Victoria .(Sagoe-Crentsil, 2002)

Figure 6. The footpath of Randwick, NSW constructed with 80% recycled aggregates.(Sagoe-Crentsil, 2002)

Field applications in regions such as Victoria and New South Wales have demonstrated that RCA produced from demolition waste can meet established road authority specifications, showing consistent grading, compaction behaviour, and mechanical performance comparable to natural aggregates. For instance, RCA sourced from commercial recycling facilities has been used in road base layers over extended monitoring periods, with test results confirming compliance with standards for abrasion resistance and durability.(Sagoe-Crentsil, 2002)

In addition to research trials, full-scale projects have incorporated substantial quantities of recycled material; some urban road upgrades have utilised tens of thousands of tonnes of recycled concrete as pavement base material, illustrating its practical viability at an industrial scale. These projects take advantage of RCA's ability to provide adequate load-bearing capacity, good drainage characteristics, and cost efficiency, while also reducing landfill waste and preserving natural resources. Consequently, pavement construction has become the primary sector in Australia where recycled aggregates are not only tested but routinely applied in real infrastructure projects, demonstrating a mature and reliable use of this sustainable material.(Sagoe-Crentsil, 2002)

These examples highlight that, despite the variability observed in laboratory conditions, recycled aggregates can be effectively reused in concrete when supported by appropriate processing, mix design, and quality control.

However, there were defects observed after construction and doing surveys. In specific:

- surface condition and pop-outs
- Cracks
- Portions showing distress
- Stains and efflorescence
- Discoloration, weathering
- Abrasion
- Staining
- Subsidence

Figure 7. The transverse cracking and settlement near joints in the footpath of Randwick, NSW. (Sagoe-Crentsil, 2002)

Chapter 2: Background

2.1 *REPLACEMENT RATIO (RR)*

To define replacement ratio, it is expressed as the weight percentage of natural aggregate replaced by recycled aggregate which is crucial to RAC performance. Given the advantages and benefits that RCA can give, maximizing the RCA replacement ratio (RR) is advantageous across these dimensions. However, higher RRs may challenge mechanical performance and durability. Therefore, design standards in different countries and guidelines place limits on RR.(Lu, 2024b)

2.1.1 *AMERICA*

The American Concrete Institute (ACI) 318-14 construction code does not explicitly include recycled concrete. However, ACI Technical Committee 555 advises using RCA in their state-of-the-art report, which discusses impurity content and RCA requirements. (committee C09, 2013; Removal and Reuse of Hardened Concrete, 2001)

Impurities	Lime Plaster	Soil	Wood	Hydrated Gypsum	Asphalt	Paint Made Vinyl Acetate
Percentage of aggregate by volume	7%	5%	4%	3%	2%	0.2%

Table 4. Requirements in ACI 555-01R for RCA(Lu, 2024a)

Materials such as municipal or industrial waste, recycled materials, and marginal materials should be thoroughly tested as they may possess undesirable physical and chemical properties. Recycled materials should be specified and evaluated according to ASTM C33, which allows recycled fine aggregates to have 0–3% to 0–5% finer material than the No. 200 sieve for abrasion-resistant concrete and 0–5% to 0–7% for non-abrasive concrete. ASTM C33 recommends using local, state, and federal test methodologies to evaluate air, water, and storage quality but does not provide specific guidance for RCA use in concrete applications.(committee C09, 2013; Lu, 2024b)

2.1.2 *AUSTRALIA*

The use of recycled concrete aggregate (RCA) in Australia is regulated by the Guide to Using Recycled Concrete and Masonry Materials (Sagoe-Crentsil, 2002).This document recommends limiting the replacement of natural coarse aggregates with RCA to a maximum of 30% in concrete production. It also establishes quality constraints, including a maximum contaminant content of 1% by mass (such as brick or wood) and a water absorption limit of 6% for coarse RCA.(Lu, 2024a)

Fine RCA is generally considered unsuitable for concrete applications due to its high-water demand. Furthermore, the guideline classifies RCA into two categories: Class 1A, which consists of well-graded material containing up to 0.5% brick, and Class 1B, which allows for up to 30% crushed brick content.(Sagoe-Crentsil, 2002)

In addition, the proportion of particles finer than 75 μm must comply with the limits specified in AS 2758.1:2014 or equivalent standards for natural or manufactured fine aggregates. Provided that these limits are not exceeded (typically 5% or 20%, depending on the aggregate type), the presence of fine particles is not expected to negatively affect performance. These requirements are summarized in Table 5.(Sagoe-Crentsil, 2002)

Requirement	AS 2758.1:2014	HB 155:2002
Water absorption	No hard limit.	Class 1A: ≤6% Class 1B: ≤8%
Saturated dry density (kg/m^3)	≥2.1, <3.2 t/m^3 (normal weight aggregate)	Class 1A: ≥2100 kg/m^3 Class 1B: ≥1800 kg/m^3
Chloride content	Combined chloride salt content <0.04% in reinforced concrete Total water-soluble chloride salt content <0.03%	
Sulfate content	Sulfate content of concrete mix ≤5% by mass of Portland cement	
Deleterious fines index	≤150	
Soundness	6% (Exposure class C)	
Light particles	≤1% (fine) ≤3% for vesicular aggregates	
Material finer than 75 μm	Coarse: ≤2%; Fine: ≤20%	
Material finer than 2 μm	≤1% (fine)	
Flakiness index	≤35%	
Replacement ratio		Class 1A: ≤30%

Table 5. Requirements in Australia standards for RCA (Sagoe-Crentsil, 2002)

2.1.3 *China*

Chinese standards classify recycled concrete aggregate (RCA) into three quality categories—Class I, Class II, and Class III—along with specific guidelines for their use in recycled aggregate concrete (RAC). The corresponding technical requirements are summarized in Table 6.(Lu, 2024a)

Requirement	Class I	Class II	Class III
Water absorption	<3%	<5%	<8%
Apparent density (kg/m^3)	>2450	>2350	>2250
Content of clay by mass	<1%	<2%	<3%
Content of clay lumps by mass	<0.5%	<0.7%	<1.0%
Porosity	<47%	<50%	<53%
Content of elongated and flaky particles	<10%		
Content of organic	Standard		
Sulfide and sulfate by mass	<2%		
Chloride by mass	<0.06%		
Other impurities	<1%		
Mass loss	<5%	<10%	<15%
Crushing Index	<12%	<20%	<30%
Replacement ratio	50~100%	30~50% for multi-story and high-rise recycled concrete buildings 50~100% for low-rise recycled concrete houses	

Table 6. Requirements in Chinese standards for RCA (Lu, 2024a)

Class I aggregates represent the highest quality and are suitable for use in both structural and prestressed concrete applications. In contrast, Class III aggregates are of the lowest quality and are restricted to non-structural uses, while Class II aggregates fall within an intermediate range of performance and applicability.(Lu, 2024a)

2.1.4 *Brazil*

The Brazilian standard NBR 15116 introduces substantial revisions to the requirements for the use of recycled concrete aggregates (RCAs). One of the most significant updates is the authorization of RCAs in structural concrete applications. According to the standard, recycled aggregates must consist predominantly of concrete waste, and only Class A construction and demolition waste (CDW) is permitted for reuse or recycling as aggregate. Furthermore, the replacement ratio (RR) for RCAs in structural Portland cement concrete is limited to 20%. Detailed specifications of these requirements are provided in Table 7. (ABNT, 2021)

Requirement	Limitation
Undesirable materials content	<1%
Clay in lumps content	<3%
Sulfate content	<0.1%
Chloride content for simple concrete	<0.2%
Chloride content for reinforced concrete	<0.1%
Chloride content for prestressed concrete	<0.01%
Water absorption	<7%
Fine (<0.075 mm) content for concrete protected from surface wear	<12%
Fine (<0.075 mm) content for concrete subjected to surface wear	<10%
Unpolished red or white ceramic content	0%
Replacement ratio	Structural Portland cement concrete: ≤20%

Table 7. Requirements in Brazil standards for RCA (ABNT, 2021)

2.1.5 *Germany*

In Germany, the use of recycled concrete aggregates (RCA) in structural applications is regulated by the Deutscher Ausschuss für Stahlbeton guideline (DAfStb, 2010), which permits the incorporation of aggregates larger than 2 mm derived from either Type 1 (primarily concrete waste) or Type 2 (mixed demolition waste) sources. The allowable replacement ratios depend on the target concrete strength: up to 25% RCA is permitted for concrete with compressive strength up to 35 MPa (B35), while higher substitution levels of up to 35% are allowed for lower-strength concrete below 25 MPa (B25). (DAfStb, 2010)

Further provisions are outlined in the amended German standard DIN 4226-100 (DIN, 2002), which authorizes the use of RCA in new concrete provided that specific classification requirements are satisfied . Within this framework, RCA is categorized into higher-quality Type 1 and lower-quality Type 2 materials, with more restrictive limitations imposed on the use of Type 2 aggregates in structural concrete applications. (DIN, 2002)

Requirement	Constituent by Mass [%]	
	Type 1	Type 2
Concrete and natural aggregates	≥90	≥70
Clinker, no porous clay bricks	≤10	≤30
Calcium silicate bricks	≤10	≤30
Other mineral materials (e.g., porous brick, lightweight concrete, plaster, mortar, porous slag)	≤2	≤3
Asphalt	≤10	≤30
Foreign substances (e.g., glass, plastic, metal, wood)	≤0.2	≤0.5
Oven dry density	≥2000 kg/m^3	≥2000 kg/m^3
Maximum water absorption (in 10 min)	10%	15%
Aggregate composition	Aggregate > 90% Bricks + Sandstone < 10	Aggregate ≥ 70% Bricks + Sandstone ≤ 30%
Replacement ratio	≤25%, with concrete strength ≤ 35 MPa ≤35%, with concrete strength ≤ 25 MPa	

Table 8. Requirements in German standards for RCA (DIN, 2002)

2.1.6 *UNITED KINGDOM*

The British standard BS 8500-2:2015+A1:2016 establishes general provisions for the use of coarse recycled aggregates in concrete, while excluding the use of fine recycled aggregates. According to the standard, recycled aggregate concrete is permitted for unreinforced applications as well as for internal and external uses, provided that the concrete is not exposed to chlorides or de-icing salts. However, its use is restricted in structural elements such as foundations and in paving applications. The maximum allowable replacement level of recycled concrete aggregate is limited to 20%, with detailed requirements outlined in Table 9. (BSI, 2016)

Requirement	Limitation
Maximum fines	≤4% by mass of particles passing the 0.063 mm sieve
Maximum acid-soluble sulfate (SO_3)	≤0.8% by mass acid-soluble sulfate
Content of: concrete, concrete products, mortar, concrete masonry units	≥90% by mass
Content of: concrete, concrete products, mortar, concrete masonry units, unbound aggregate, natural stone, hydraulically bound aggregate	≥90% by mass
Content of: clay masonry units (i.e., bricks and tiles), calcium silicate masonry units, aerated non-floating concrete	≤10% by mass
Content of bituminous materials	≤5% by mass
Content of other materials: Cohesive (i.e., clay and soil) Miscellaneous metals, ferrous and non-ferrous Non-floating wood, plastic, and rubber Gypsum plaster and glass	≤1% by mass
Floating material by volume	≤2 cm^3/kg
Replacement ratio	≤20%

Table 9. Requirements in U.K. standards for RCA (BSI, 2016)

The compressive strength of concrete mixed with RCA is influenced by various factors, including the replacement ratio, water-to-cement ratio, cement type and admixtures, aggregate size and shape, curing moisture conditions, temperature, and loading ratio during testing. Early studies indicate that the compressive strength of RAC is typically 0–30% lower than natural aggregate concrete (NAC) due to the replacement ratio and water-to-cement ratio. Recent studies on the effect of substitution rate on compressive strength have reached similar conclusions, as shown in figure 3.(Lu, 2024b)

It is important to understand the behaviour of RAC by comparing different mechanical and physical properties with NAC in both fresh and hardened phases.

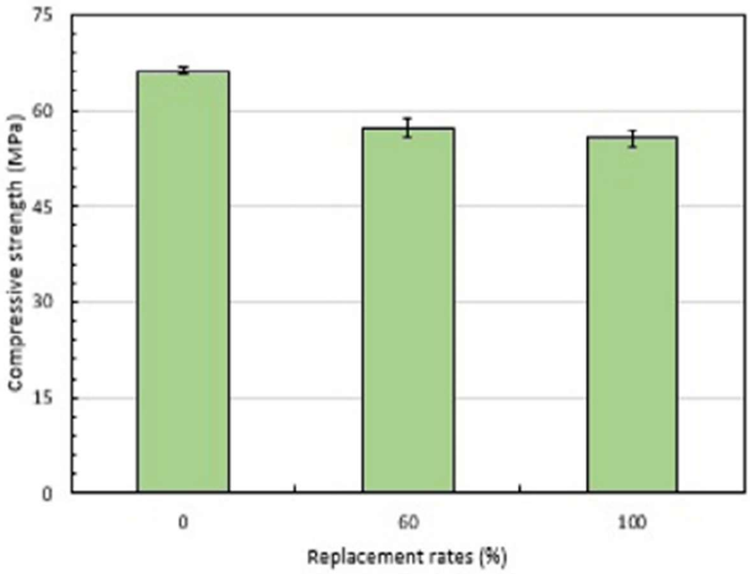


Figure 8. Compressive strength versus replacement rates at 28 days. These values might not be constant in every experimental work since there is diversity in the type of aggregates. (Lu, 2024a)

According to a study by (Wang et al., 2021a) the relationship between the compressive strength and the replacement ratio, is indicated by figure 4.

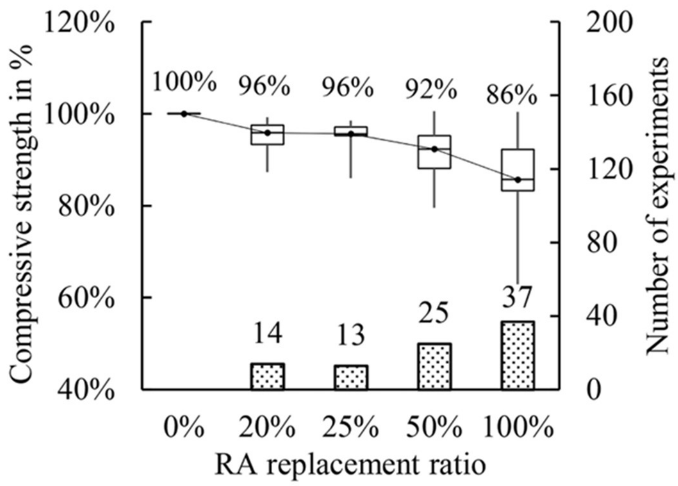


Figure 9. Relationship between compressive strength and the increasing replacement ratio.(Wang et al., 2021b)

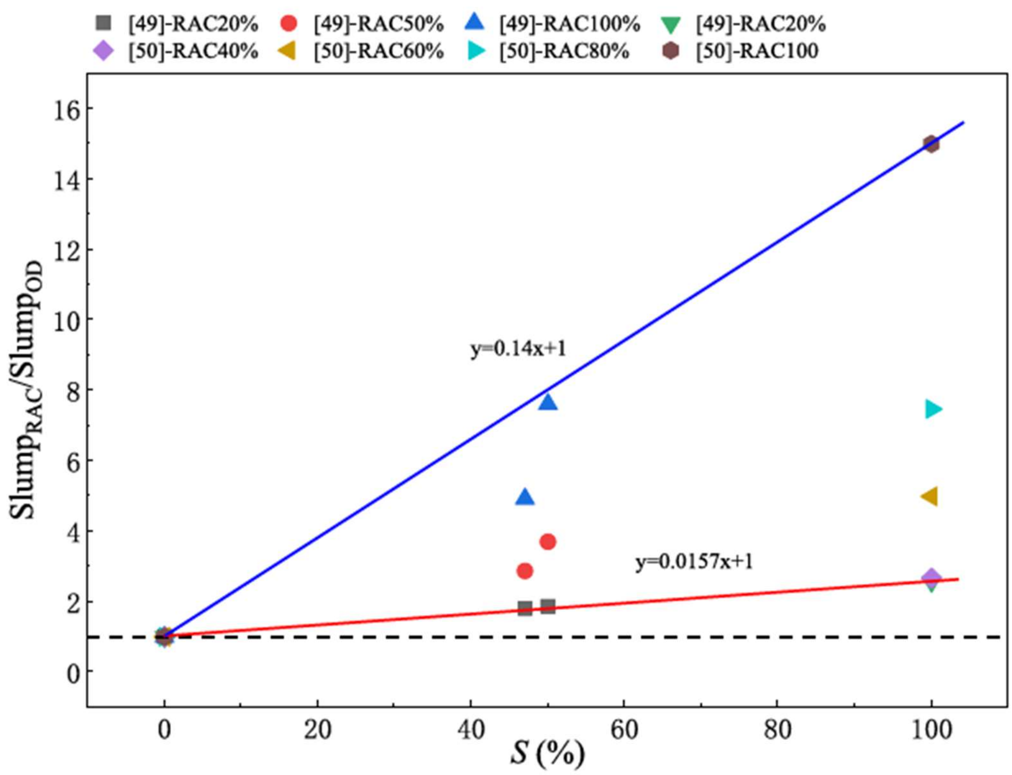
2.2 *Mechanical properties of RAC regarding the influence of moisture*

2.2.1 *Workability of R.A.C*

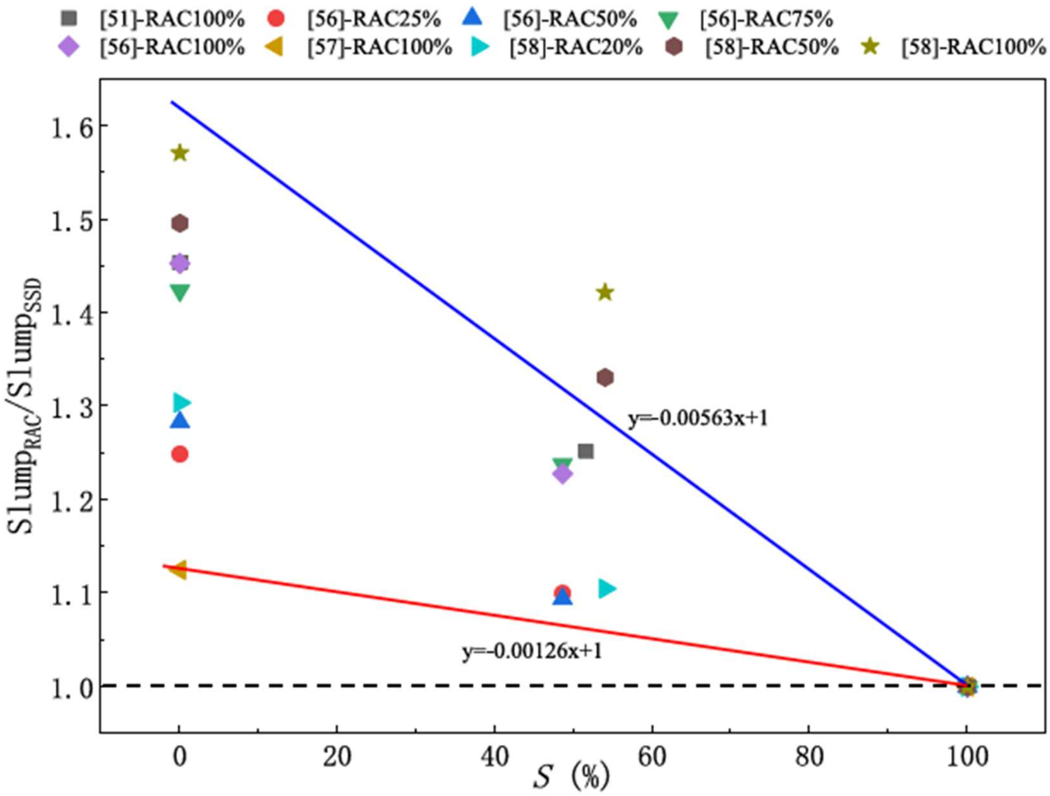
The poorer workability of RAC than that of New Aggregate Concrete (NAC) has already been widely reported by previous studies. The poor fluidity of fresh RAC is mainly due to the large water absorption of RA which could be 2.3 to 4.6 times higher than that of new aggregate. Considering this, many researchers studied the effects of the moisture states of RA on the workability of the prepared RAC mixture. Studies have found that at a fixed mixing water supply, the initial slump of RAC prepared with the oven-dried (OD) RA was the smallest among all those prepared with RA at different moisture states. Given that the moisture states of RA was expressed as the saturation degree, S, the relative slump of RAC over the varying saturation degrees of RA compared to the slump of RAC with the OD RA (namely, Slump), can be illustrated by figure 5(a).The saturation degree S can be calculated by following equation below.(Zhang et al., 2022a)

$$S = \frac{M}{W} \times 100\%$$

A larger S means the water content of RA is high. Where “M” and “W” represent the moisture content of RA and the water absorption of RA, respectively. Test results in figure 5(a) show that at a fixed mixing water supply, the slump of RAC increases as the S of RA increases. This is reasonable because dry RA can absorb water from the cement slurry during the mixing procedure, which leads to a loss in the free water and thereby reducing the fluidity of the fresh RAC mixture.



(a)



(b)

Figure 10. Slump of RAC prepared with RA at different S and different water supply schemes: (a) at a fixed mixing water supply; and (b) at a fixed total water supply, respectively.(Zhang et al., 2022b)

On the other hand, the wet RA will absorb less water from the cement slurry than the dry RA, due to the presence of the initial water contained in RA. Clearly, the cement slurry would be more flowable by using the highly saturated RA which thereby benefits the workability of the fresh RAC. Figure 5(a) also shows that the evolution of the relative slump of RAC compared to that of the reference RAC prepared with the OD RA falls between two lines by applying the linear fitting between the slump data and the saturation degree. The two lines can be expressed by the equations below, respectively, as given by figure 5(a).

$$Y = 0.14X + 1$$
$$Y = 0.0157X + 1$$

The indicator 0.14 and 0.0157 represents the increasing speed of the relative slump of the RAC mixture with the rise of the saturation degree of RA and quantify the effects the moisture states of RA on the slump of RAC, given that the total mixing water supply is kept being constant.(Zhang et al., 2022a)

Regarding the case at the fixed total water supply it is reported that the initial slump of RAC underwent a decrease with the increase of the water content of RA. Different from the case at a fixed mixing water supply, the smallest slump was observed from the RAC group prepared with

RA at the Surface Saturated Dry (SSD) condition. Taking the slump of the RAC group with the SSD RA (i.e., Slump SSD) for the reference, the evolution of the relative slump of RAC mixture over the saturation degree of RA can be summarized in Figure 5(b). As is seen from figure 5(b), the relative slump of RAC undergoes a decrease with the increase of the saturation degree of RA, at the fixed total water supply. Similarly, the decreasing is almost linear and the relative slump data falls between the two lines shown in figure 5(b), as expressed by $y = 0.00563x + 1$ and $y = 0.00126x + 1$, respectively. At a fixed total water supply, the amount of the mixing water would vary along with the initial water content of RA. The larger initial saturation degree (i.e., S) of RA indicates that more water is pre-absorbed by RA, which signifies that less mixing water is added during the concrete mixing procedure. This may probably render the cement slurry dry, so the RAC slump demonstrates a downward trend as S increases, as illustrated by figure 5(b). Note that under this scenario, it is also likely that the initially dry RA would absorb more water from the cement slurry during the concrete mixing, which could lead to the loss in the mixing water so the slump of RAC should have been adversely affected. However, it is suggested that the loss in the mixing water by the RA absorption behaviour should be limited since the mixing duration is relatively short.

Therefore, the adverse effects on the slump of RAC by using the dry RA at the fixed total water supply would not exceed the benefits of the initially high mixing water. This explains why the slump of RAC prepared with the dry RA is still higher than that with the saturated RA in figure 5(b).(Zhang et al., 2022a)

2.2.2 COMPRESSIVE STRENGTH

Compressive strength is widely used as the basic indicator for the mechanical properties of concrete. It is now widely accepted that the compressive strength of RAC is apparently inferior to that of NAC when more than 30% NA was replaced by RA. As for the RAC compressive strength at varying moisture states of RA, many studies have confirmed that the influence indeed exists, but the conclusions are quite different from one another.(Zhang et al., 2022a)

Most of the test results show that using the partially saturated RA is beneficial for the compressive strength of RAC, while using the completely saturated RA (i.e., the SSD RA) or completely dry RA (i.e., the oven-dried RA) may lead to obvious loss in the compressive strength. For example, RA at three different moisture states (Air-dried, Oven-dried and Surface-saturated dried) is used to prepare RAC for the measurement of compressive strength. The RA replacement ratio was set to be 100% and three duplicated cubes with the dimensions of 100 mm were cast for each RAC group by keeping the mixing water supply the same. The specimens were demoulded after 1 day and then they were cured in water at 27 ◦ C for 90 days. It was found that the compressive strength of RAC prepared with the AD aggregate was 15.6% to 23.8% higher than that with the OD or SSD aggregates regardless of ages, meanwhile the compressive strength by taking the SSD aggregate was the lowest.(Zhang et al., 2022a)

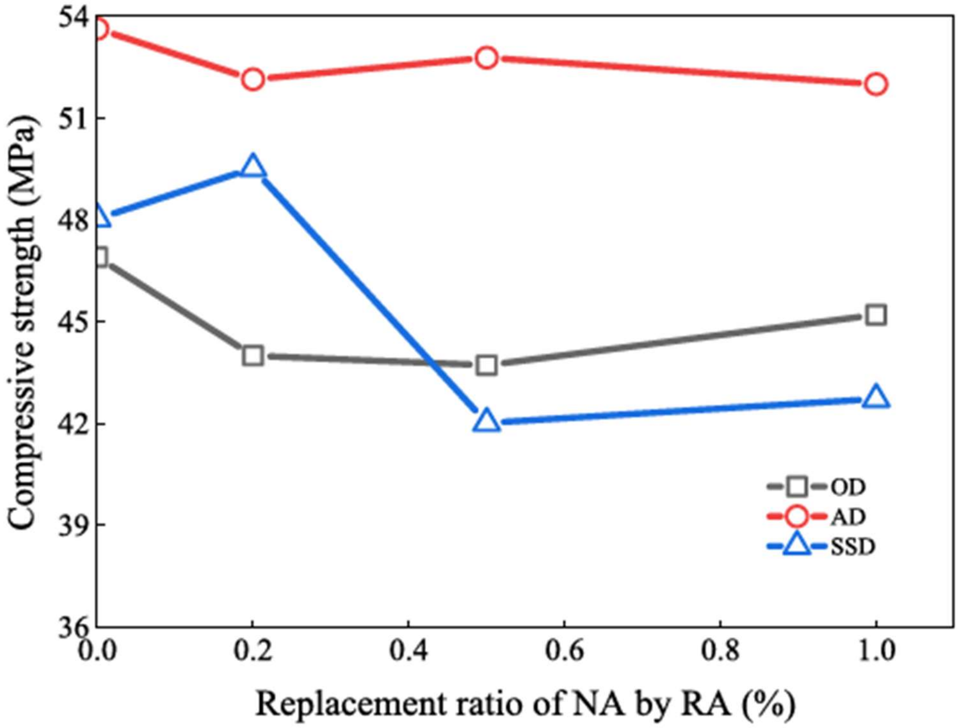


Figure 11. The compressive strength of RAC prepared with RA at three different moisture states. (OD: Overdried, AD: Air-dried , SSD: Surface-Saturated Dried

There exists a large divergence in current viewpoints regarding the influence of the moisture state of RA on the compressive strength of RAC. The possible reasons for this divergence include the deviation in the RA quality attributed to the different contents and porosity of the old cement mortar, and the diverse mixture proportions and mixing procedures as taken by each certain study. Moreover, the water absorption and desorption process of RA at different moisture states could be complicated, which can also increase the divergence among different studies.(Zhang et al., 2022a)

2.2.3 ELASTIC MODULUS

The elastic modulus of RAC is reported to be 15% to 45% lower than that of NAC, which is mainly due to the poor strength and elastic modulus of RA with the presence of the porous old mortar. Some scholars have explored the elastic modulus of the RAC by using RA at different aggregate moisture states, but overall, these studies are rare.(Zhang et al., 2022a)

2.2.4 SHRINKAGE

Most published studies claimed that there are significant differences between RAC and NAC in the shrinkage (including both the drying shrinkage and the autogenous shrinkage). As for the drying shrinkage, it is reported that the RAC presented 15%- 80% higher drying shrinkage than that of NAC.A model is proposed to describe the drying shrinkage of RAC at the varying strengths of the parent concrete and claimed that the drying shrinkage of RAC was effectively reduced by increasing the parent concrete strengths. The results showed that the drying shrinkage of RAC prepared with the OD RA was the largest, followed by that with the SSD RA, while the drying shrinkage of RAC prepared with the partially saturated (80% S) RA was the smallest, given a consistent total water supply. According to other similar results, it is claimed that the drying shrinkage of RAC with the pre-wetted RA was less than that with the dry aggregate at a fixed total water supply, while it was the opposite when the mixing water supply was the same. Using the dry or saturated RA can also lead to greater drying shrinkage of RAC compared to that using RA at a natural state, namely, at a partially saturated state. One study compared the drying shrinkage between two RAC groups prepared with the pre-saturated RA and the naturally dried RA, at different water supply schemes. They found that the drying shrinkage of RAC prepared with the SSD RA after the pre-wetting operation was lower than the other concrete group at the same supply of total water (see figure 7.).(Zhang et al., 2022a)

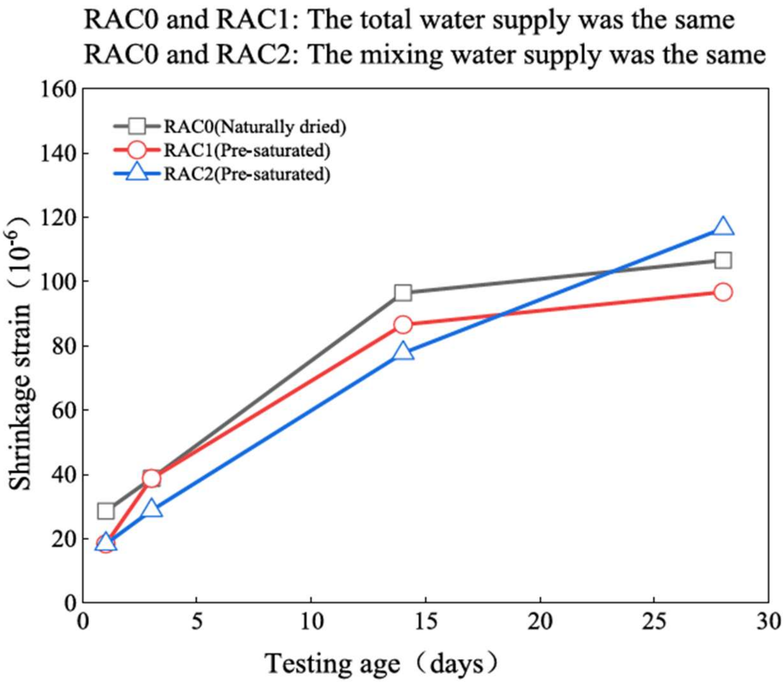


Figure 12. comparison of shrinkage strain during different ages

2.2.5 *DURABILITY*

It is now well accepted that the durability should be an important concern for RAC's use in reinforced structures rather than the mechanical properties. Most studies have confirmed the inferior resistance of RAC to the ingress of hazardous substances (e.g., the chloride ions, the sulphate ions, as well as the water in the alkali-aggregate reactions and the frost actions) in comparisons with that of NAC. This has rendered a great difficulty for RAC's wide application in the structural use. Basically, the references regarding the influence of the RA moisture states on the durability of RAC are quite limited in the quantity, compared to those dealing with the mechanical performance of RAC. Some studies reported that the moisture state of RA had a significant impact on several representative durability indexes of RAC. The performance of RAC subjected to the freezing-thawing cycles is studied at the varying moisture states of RA (the saturation degree of RA was 0%, 88.1%, 89.5%, and 100%, respectively). It is found that, at a consistent mixing water supply, it was the concrete group prepared with the completely saturated RA that presented the worst freezing-thawing resistance. Using the partially saturated

RA can improve the freezing-thawing resistance of RAC compared to that using the dry or completely saturated RA.(Zhang et al., 2022a)

2.3 *CARBONATION TREATMENT*

One of the important issues of using RAC is the PH value and alkalinity of it which leads to an early corrosion of steel. A study through experimental works indicates that carbonation treatment has potentials to change many properties of RCA including a decrease in the PH value, considering that uncarbonated RCA exhibited a higher water absorption than the carbonated RCAs.(Zhan et al., 2019)

Physical properties of RCA before and after carbonation.

	Water absorption, %	Moisture content, %	Apparent density, Kg/m^3
Uncarbonated RCA	7.52	2.30	2636
Carbonated RCA	5.76	1.90	2700

Table 10. Physical properties of RCA and carbonated RCA

After observing the corrosion test results showing the polarization resistance of RAC and CRAC over the 12 drying and wetting cycles. It can be found that before the drying and wetting cycles started, a higher polarization resistance was observed in the RAC than that in the CRAC. This is probably due to that the old cement mortar attached on the RCA increased the alkalinity of the RAC. While the alkalinity of CRCA decreased after the carbonation treatment, because the carbonation treatment could reduce the free alkali metal and the hydroxyl ions concentrations in the CRCA and thus might also lower the pH in the new concrete, which weakened the passivation of the steel reinforcement, and decreased the chlorine ion threshold. But polarization resistance of RAC decreased rapidly after the 11th drying and wetting cycle. It meant that the steel embedded in RAC was corroded.(Zhan et al., 2019)

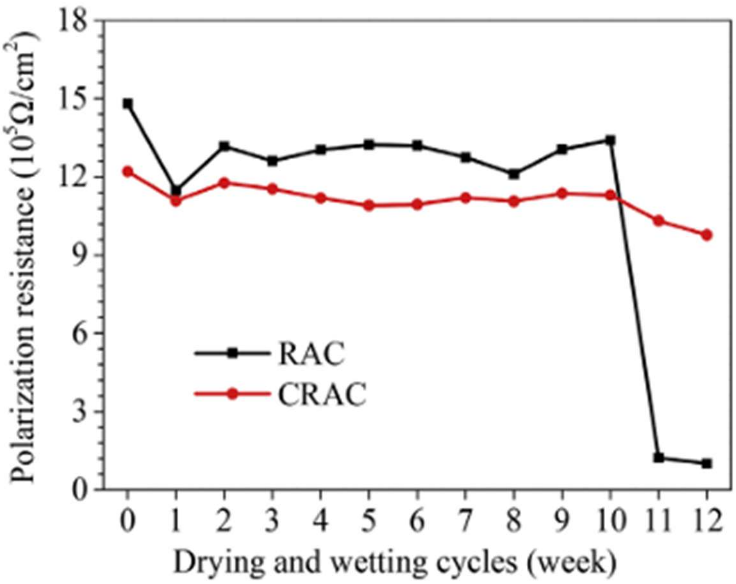


Figure 13. Polarization resistance of steels in RAC and CRAC over 12 drying and wetting cycles.

Meanwhile there was no obvious changes in polarization resistance of CRAC over this drying and wetting cycles, reflecting the steel in CRAC was still passivated. This was because aggressive agents, such as Cl^-, O_2 and H_2O, were more accessible to the steel of the RAC prepared with uncarbonated RCA, which initiated the corrosion of steel at an earlier time. Meanwhile, the carbonation treatment enhanced the impermeability of the old cement mortar adhered to the RCA, and to some extent further improved the resistance to the penetration of deleterious species into the concrete. Therefore, it has been demonstrated that the carbonation modification of RCA improved the protection of steel from corrosion.(Zhan et al., 2019)

2.4 *METHODS FOR ENHANCING THE PERFORMANCE OF R.A.C*

Although recycled aggregate concrete (RAC) generally demonstrates lower performance compared to natural aggregate concrete (NAC), its potential for promoting sustainability through the reuse of materials and industrial by-products is significant. Consequently, RAC should not be disregarded; rather, research efforts have focused on improving its performance to meet structural standards. Many approaches target the enhancement of the interfacial transition zones (ITZs) between aggregate and binder, which are negatively influenced by the presence of adhered old mortar (Ho et al., 2018). Strategies include removing the residual mortar, coating the old mortar to mitigate its effects, modifying mix designs to account for attached mortar, and partially replacing Portland cement with alternative industrial by-products.(Upshaw & Cai, 2020)

2.4.1 *REMOVAL OF OLD CEMENT MORTAR FROM RECYCLED AGGREGATES*

Several methods have been developed to remove part or all the old cement mortar from recycled aggregates, resulting in improved RAC performance. For instance, ultrasonic cleaning has been used to enhance the bond between aggregate and new cement paste, producing modest compressive strength gains of 3% and 7% at 7 and 28 days, respectively (Katz, 2004). Similarly, microwave heating improved compressive and splitting tensile strengths by 5–12% compared to untreated aggregates (Choi et al., 2014). Acid pre-soaking treatments have also shown promise; Tam et al. (2007) and Ismail and Ramli (2013) reported strength improvements using hydrochloric, sulfuric, and phosphoric acids. Moreover, Purushothaman et al. (2015) found that a combination of sulfuric acid treatment and mechanical heating–scrubbing reduced water absorption and improved aggregate quality.(Upshaw & Cai, 2020)

Despite these promising laboratory results, large-scale implementation faces practical limitations. Many of these techniques require additional processing stages, making integration into existing concrete production plants costly and logistically challenging. Methods such as microwave heating and ultrasonic cleaning are also time-consuming and less suited for industrial-scale application. As a result, research has increasingly shifted toward optimizing RAC mixing processes as a more practical means of performance enhancement.(Upshaw & Cai, 2020)

2.4.2 *COATING OF R.A.C*

An alternative approach to improving the performance of recycled aggregate concrete (RAC) involves coating recycled aggregates to seal and strengthen existing cracks in the adhered mortar. This method aims to enhance the interfacial transition zone (ITZ) between recycled aggregates and new mortar. Tam et al. (2005) proposed a double-mixing method, which fills pores and cracks within the ITZ, resulting in improved compressive strength. Building on this, Kong et al. (2010) developed a triple-mixing method that incorporates pozzolanic materials such as fly ash, slag, and silica to coat the aggregate surface. This modification further enhanced compressive strength and chloride resistance compared to the double-mixing method. Other innovative coating strategies have also been explored. Kareem et al. (2018) introduced a double-coating system, applying an initial layer of cement–slag paste followed by a coating of Sika Tite-BE. Although their study focused on hot-mix asphalt (HMA), the improvements in moisture resistance and stiffness are relevant to RAC, as similar benefits could enhance durability. Zhang et al. (2018) demonstrated that coating aggregates with sulphoaluminate cement (SAC) reduced water absorption and crushing value, while increasing workability, compressive strength, density, and chloride resistance. The addition of basalt powder (BP) to SAC further improved aggregate crushing value, compressive strength, and workability. Similarly, Zhihui et al. (2013) reported an optimal SAC coating thickness of 0.035 mm and observed that increasing the water-to-cement ratio in the coating paste unexpectedly led to higher compressive strength. (Upshaw & Cai, 2020)

Not all coating techniques have yielded positive results. For example, Zhu et al. (2013) found that silane-based polymer coatings reduced water absorption but also lowered compressive strength, likely due to hydrophobic effects from silane hydrolysis that inhibited cement hydration in localized areas (Spaeth et al., 2008). (Upshaw & Cai, 2020)

Overall, coating recycled aggregates has shown considerable potential for improving RAC performance, especially since coating materials can be treated as admixtures, making large-scale application feasible. However, most studies have concentrated on water absorption and compressive strength, while other important properties—such as corrosion resistance, coefficient of thermal expansion, density, splitting tensile strength, Young's modulus, and bond strength—remain underexplored. Furthermore, most of the research has focused on recycled coarse aggregates (RCA), with limited literature on recycled fine aggregates (RFA). Notably, Ho et al. (2018) found that coating RFA with slag significantly enhanced concrete performance.(Upshaw & Cai, 2020)

2.5 *Microbially Induced Carbonate Precipitation (M.I.C.P) treatment*

Microbially induced carbonate precipitation (MICP) is a technique that improves recycled aggregates (RA) by filling their pores and cracks with calcium carbonate ($CaCO_3$). This process works in a similar way to carbonation, making the aggregates denser and less absorbent. Concrete made with MICP-treated RA can achieve about 11% higher splitting tensile strength than natural aggregate concrete (NAC) and similar compressive and flexural strengths.

Researchers have developed ways to make MICP more effective. For example, adding mesoporous silica nanoparticles as carriers for urea helps control how $CaCO_3$ forms, increasing its strength and bond to RA. Pre-treating RA with chitosan before MICP makes the $CaCO_3$ spread more evenly, which increases density by 2.5%, reduces water absorption by 20.6%, and lowers the crushing index by 18.1%. Using sodium alginate has a similar effect, helping bacteria spread evenly and form a network that improves bond strength and reduces water absorption.

Some studies have found that MICP can also create other minerals, such as thaumasite and C–S–H, which make the concrete denser. This can even be done using waste slurry from livestock farming, which improves concrete and recycles agricultural waste.

However, MICP is not yet widely used because bacteria need certain temperatures and pH levels to work effectively. A similar method, enzyme-induced carbonate precipitation (EICP), uses enzymes instead of bacteria but has the same limitations. To overcome this, some researchers have developed non-bacterial methods, such as soaking RA in urea and calcium acetate, then heating it so that aragonite forms inside the pores. This improves strength, reduces water absorption, and increases resistance to chloride penetration. Another new approach, biomimetic carbonate precipitation, uses molecules like L-aspartic acid to form stable and strong $CaCO_3$ crystals, showing good potential for improving RA. (Bai et al., 2025)

Chapter 3: Characteristics of R.A.C

3.1 *CODE APPROACH*

The use of RAC in structural and non-structural applications is governed by various design codes and standards. Different countries have developed guidelines to address the unique properties of recycled aggregates. As an example, according to ASTM (American Society for Testing and Materials) ASTM C33 provides specifications for aggregates. ASTM C618 and C1240 provide guidance for supplementary cementitious materials often used with RAC. Moreover, it emphasizes testing recycled aggregates for physical and chemical properties, including water absorption, density, and contamination(ASTM international, 2018). The American Concrete Institute's ACI 318 provides guidelines for the design and construction of structural concrete. While it doesn't explicitly address recycled aggregates, it offers provisions that can be applied to RAC, such as Strength reduction factors since Adjustments to strength reduction factors may be necessary when using recycled aggregates, considering their typically lower strength compared to natural aggregates. Also, durability considerations and enhanced durability measures such as increased cement content or the use of supplementary cementitious materials, may be required to compensate for potential weaknesses in RAC.(American concrete institute, 2019)

According to EN Standards (European Norms), EN 206 provides guidance for the production and specification of concrete with recycled aggregates. There are 3 key considerations to qualify the aggregates of concrete which are so important in our case to be studied. Firstly, recycled aggregates must meet specific quality criteria, including limits on impurities and mechanical properties. Secondly, Concrete made with recycled aggregates must be classified according to exposure classes, considering factors like freeze-thaw resistance and sulphate attack. Lastly, EN standards introduces performance-based approach enabling the use of recycled aggregates if the concrete meets specified performance criteria, such as compressive strength and durability.(European Committee for Standardization, 2016)

British Standards (BS 8500) include provisions for partial replacement of natural aggregates and Japanese and Australian codes also define specific limits and treatments for RAC.

The Equivalent Concrete Performance Concept allows for deviations from standard concrete compositions, provided the resulting concrete demonstrates equivalent or superior performance in key areas:

- Compressive Strength: Concrete made with recycled aggregates should achieve compressive strengths comparable to those made with natural aggregates.
- Durability: The concrete must exhibit similar or better resistance to factors like carbonation, chloride migration, and freeze-thaw cycles.
- Environmental Impact: The use of recycled aggregates should contribute to reduced environmental impact, aligning with sustainability goals.

This concept facilitates the integration of recycled aggregates into concrete mixes, promoting sustainability without compromising performance.

Despite the availability of various standards, challenges remain in the widespread adoption of RAC:

- Variability in Recycled Aggregate Quality: The quality of recycled aggregates can vary significantly depending on the source material and recycling process, complicating standardization efforts.

- ➢ Lack of Uniform Testing Procedures: Inconsistent testing methods for recycled aggregates can lead to discrepancies in performance assessments.
- ➢ Need for Modified Mix Designs: Traditional concrete mix designs may not be directly applicable to RAC, necessitating adjustments to account for the unique properties of recycled aggregates.

3.2 *Physical characteristics*

RCA typically exhibits lower density and higher porosity compared to natural aggregates due to the presence of adhered cement paste, which can constitute up to 30–60% of the aggregate volume. This adhered mortar increases the water absorption capacity of RCA, often resulting in water absorption rates 20–50% higher than those of natural aggregates. Consequently, RAC requires higher water content or the use of chemical admixtures to achieve workability comparable to NAC.(Mandal & Shiuly, 2025; Thomas et al., 2013)

3.3 *Fresh-state properties*

The fresh-state properties of RAC, particularly workability, are negatively impacted by the higher porosity and angularity of RCA particles. Several studies indicate that RAC requires approximately 10% more water to achieve similar slump levels compared to NAC, though this can be mitigated by superplasticizers or supplementary cementitious materials.(Mandal & Shiuly, 2025; Thomas et al., 2013)

3.4 *Mechanical characteristics*

3.4.1 *Compressive strength*

RAC exhibits compressive strength reductions of 5–25% depending on the quality and replacement level of RCA. Nevertheless, up to 50–60% replacement can yield compressive strength within acceptable structural ranges.(Thomas et al., 2013)

3.4.2 *Tensile strength and modulus of elasticity*

Both parameters decline compared to NAC due to a weaker interfacial transition zone (ITZ). Evangelista & de Brito (2007) reported reductions of up to 20% in tensile strength and 10–15% in modulus of elasticity.(Evangelista & de Brito, 2007)

3.5 *Durability characteristics*

3.5.1 *Permeability and water absorption*

Higher porosity increases permeability, resulting in greater susceptibility to ingress of harmful agents such as chlorides and carbon dioxide.(Thomas et al., 2013)

3.5.2 *Carbonation resistance*

Carbonation depth in RAC tends to be greater than in NAC, though the use of fly ash, silica fume, or slag can mitigate this effect.(Thomas et al., 2013)

3.5.3 *Freeze–thaw resistance*

With proper air entrainment, RAC can achieve freeze–thaw resistance comparable to that of NAC.(Thomas et al., 2013)

3.6 *PERFORMANCE PARAMETERS OF R.A.C*

3.6.1 *STRUCTURAL PERFORMANCE INDICATORS*

Compressive Strength is the primary structural indicator and dictates the applicability of RAC in load-bearing members. The reduction is closely tied to RCA quality and replacement ratio. Tensile Strength and Modulus of Elasticity directly influence cracking behaviour and deformation under load. Lower modulus values imply increased deflection for equivalent loads.(Evangelista & de Brito, 2007)

3.6.2 *DURABILITY PERFORMANCE INDICATORS*

Water Absorption & Permeability are critical for durability assessment, influencing resistance to freeze–thaw cycles, sulphate attack, and chloride ingress.(Poon et al., 2004)

Carbonation and Chloride Penetration are particularly important in reinforced concrete applications, as they determine the potential for reinforcement corrosion.(Thomas et al., 2013)

3.7 *PROPER-GRADING APPROACH TO R.A.C USING FULLER AND BOLOMEY CRITERIONS*

The production of Recycled Aggregate Concrete (RAC) typically relies on supplementary cementitious materials or chemical admixtures to compensate for the intrinsic weaknesses of recycled aggregates, such as high porosity and residual mortar content. However, in a practical, on-site context, it is possible to minimize external inputs by focusing exclusively on the granulometry and quality of recycled aggregates.

The central hypothesis is that, by ensuring optimal particle size distribution and aggregate quality, it is possible to produce structurally and durably adequate concrete without new substances. This approach emphasizes the Foller and Bolomey criterions as critical selection tools. Therefore, this research supports the hypothesis that proper grading optimization may represent a low-cost, sustainable, and industrially feasible strategy for improving RAC performance, particularly in decentralized urban recycling applications such as those investigated in Genoa.

3.7.1 *SIEVE ANALYSIS*

Sieve analysis is a fundamental laboratory technique used to determine the particle size distribution of aggregates. A sample of air-dried aggregate is graded by shaking or vibrating a nest of stacked sieves, with the largest sieve at the top, for a specified time, so that the material retained on each sieve represents the fraction coarser than the sieve in question but finer than the sieve above. It provides the cumulative percentage of aggregate passing through a series of standard sieves. For recycled aggregate concrete (RAC), this analysis is essential because recycled aggregates often have irregular shapes, adhered mortar, and higher variability than natural aggregates. Thus, sieve analysis helps identify where the recycled aggregate grading deviates from ideal grading curves, allowing for mix adjustments to optimize density and performance.

By comparing actual RAC gradation with the curves Fuller and Bolomey, the mix designer can decide whether to blend finer or coarser fractions or process aggregates to achieve the optimal grading range. (A.M. Neville and J.J Brooks, 2010)

Figure 14. The sieve analysis process which is also called the granulometry test to understand the distribution of the aggregates considering the size and dimensions. The pictures are taken in the laboratory of the university of genoa.

3.7.2 *METHOD*

- A known mass of aggregate is placed on the top sieve of a stack arranged in decreasing size.
- The stack is mechanically shaken.
- The mass retained on each sieve is measured.
- The cumulative percentage passing through each sieve is calculated as:

$$P(d) = 100 \times \frac{\sum_{i=1}^{n} m_i}{M_{total}}$$

P(d) = cumulative percentage passing through sieve of size (d)
m_i = mass of aggregate retained on sieve i
M_{total} = total mass of sample
Graphically, sieve analysis is plotted as a cumulative passing curve with particle size (mm) on the x-axis and cumulative percentage passing on the y-axis.

3.7.3 *FULLER'S LAW (1907)*

Fuller proposed an ideal aggregate grading curve to maximize packing density, minimize voids, and improve workability. This curve is expressed as a power function of particle size.

$$P(d) = 100 \times \left(\frac{\mathrm{d}}{D_{max}}\right)^{n}$$

P(d)= cumulative percentage passing sieve of size d
D_{max}= maximum particle size
n= exponent, typically 0.45 for dense concrete

The curve is convex, starting from 0% at the smallest sieve and reaching 100% at D_{max} Fuller's curve serves as a benchmark. Actual aggregate gradation can be compared to assess packing efficiency.

Recycled aggregates tend to have more fines and irregular shapes and adjustments may be needed to achieve a gradation that approximates the Fuller curve, ensuring higher packing density and lower porosity.

3.7.4 *Bolomey's law (1929)*

Bolomey extended Fuller's law to account for the optimal volumetric proportion of each particle size. The Bolomey formula also relies on sieve analysis data:

$$P(d) = \left(\frac{\mathrm{d}}{\mathrm{D}_{max}}\right)^{1/2} \times 100$$

P(d) = cumulative percentage passing
D = sieve size
D_{max} = maximum aggregate size

Bolomey's formula uses an exponent of 0.5 (or 1/2), slightly different from Fuller's 0.45. It provides a practical approximation for gradation curves that optimize density and workability. The Bolomey curve is slightly steeper than Fuller's, giving more weight to larger aggregates. In combination with sieve analysis, it helps engineers select aggregate proportions that fill voids efficiently. Using Bolomey's formula for 100% recycled aggregates helps minimize voids created by irregularly shaped recycled particles.

Gradation curves can be plotted alongside experimental sieve analysis to determine adjustments in coarse-to-fine ratios.

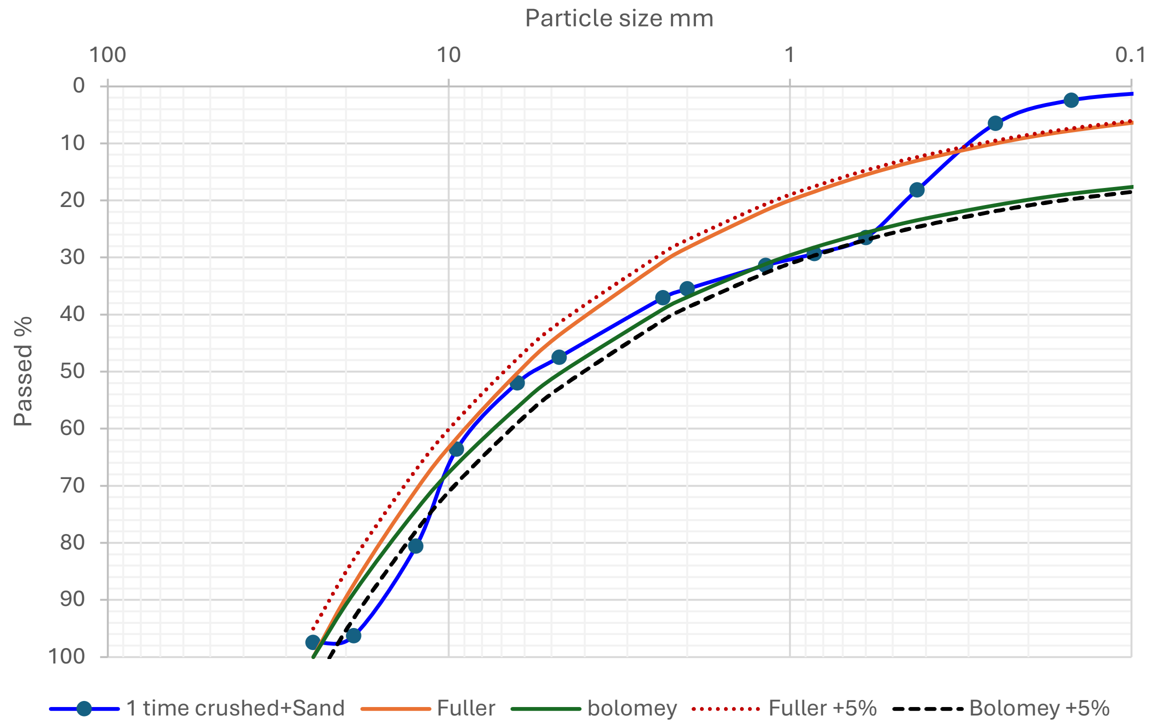


Figure 15. Here is an example of a sieve analysis of a type of aggregate to show the performance of its granulometry considering the curves of fuller and bolomey. The more our curve fits between the two criterions, the better performance we would expect.

Chapter 4: Experimental Campaign

4.1 *Parameters to be investigated*

4.1.1 *Water absorption test*

Water absorption, which represents the capacity of aggregates to absorb moisture into their pores is a critical property. This parameter directly affects the water-to-cement ratio, workability, and long-term durability of concrete. Therefore, understanding the water absorption capacity of aggregates is essential for proper mix proportioning and performance prediction. To begin, the aggregates which in our case are mixed debris and broken concrete must be weighed in the dry state. The measured weight of dry aggregate (both coarse and fine) is denoted as W_1. Then, the aggregates are immersed in water for 1 hour and after the immersion, the water is removed, and they are air-dried with room temperature. The partial wet aggregate which is saturated surface-dry (SSD) is weighed once more, and the measured weight is denoted as W_2. The formula for evaluation the water absorption percentage will be:

$$\text{Water absorption}=\{(W_2-W_1)/W_1\} *100$$

Figure 16. The aggregates are immersed in water for 1 hour

Figure 17. The water is removed, and wet aggregates are weighted

4.1.2 *DENSITY OF THE MATERIALS*

Density is a fundamental physical property of aggregates and concrete that significantly influences fresh and hardened properties. The unit is Kg/m^3 and generally it indicates how well particles are packed together and eventually this parameter affects mix proportioning and workability. In recycled aggregates, density is often lower than in natural aggregates due to:

- Porous adhered mortar from the original concrete.
- Microcracks from mechanical crushing.
- Heterogeneous composition (presence of brick, plaster, etc.).

4.1.3 *COMPRESSIVE STRENGTH TEST*

the testing methodologies are employed in evaluating the compressive strength characteristics of concrete cube specimens prepared in accordance with relevant standards. The tests were carried out under controlled laboratory conditions to ensure consistency and reliability of results. Compressive strength test is employed to determine the compressive strength of concrete cubes at specified curing ages which are 4,7,14, 28, 90 and 120 days after setting. In accordance with standards curing practices the specimens are cast and cured for these specific ages.

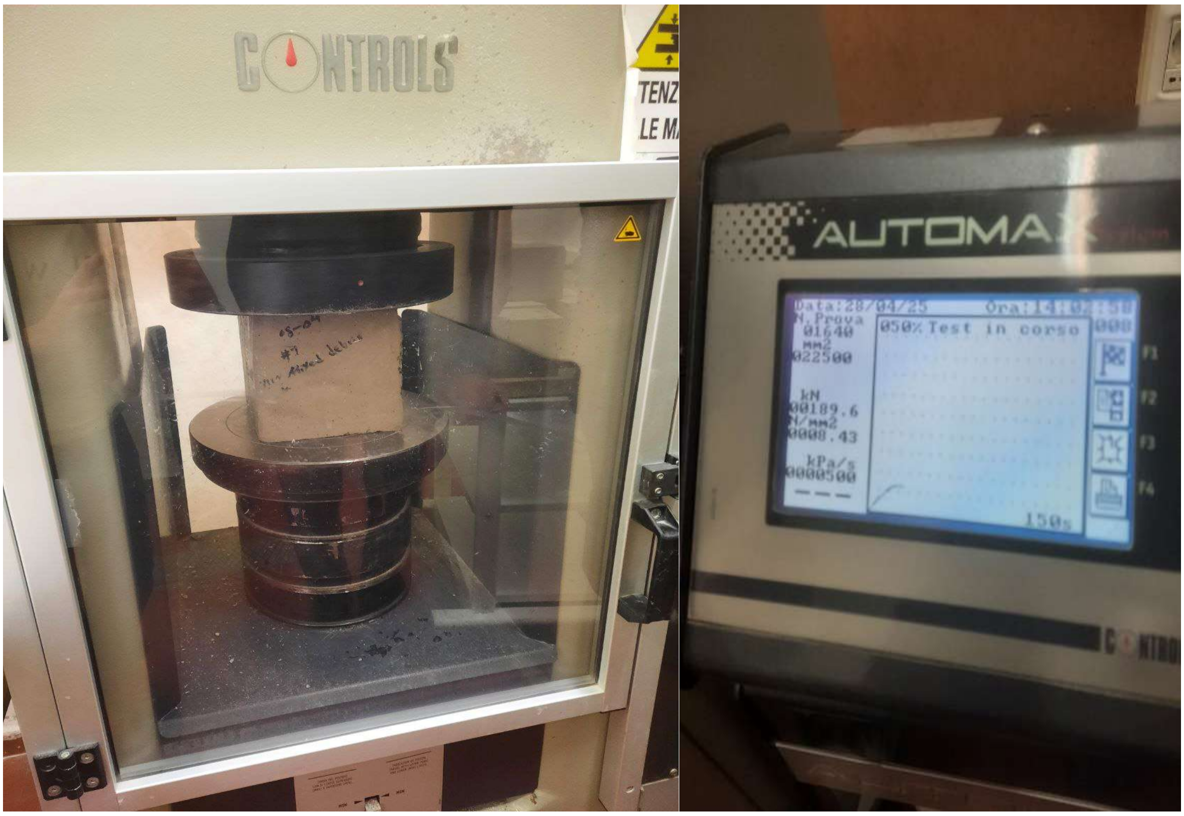


Figure 18. The compression test machine. pictures are taken from the laboratory of the university of Genoa.

The specimens' dimensions are 150 mm width, 150 mm length and 150 mm height and they are extracted approximately in 1 or 2 days after setting of concrete. The extraction waiting time varies since the time needed for the moisture and humidity of concrete to be vapored is different. Each cube was removed from the curing tank, surface water was wiped off, and the dimensions were measured to ensure conformity.

Figure 19. Making the specimens in the framework, extracting them, immersing them in water and finally testing them. All pictures are taken in the laboratory of university of genoa

The specimen was centred on the lower platen of the compression testing machine. The load was applied axially and uniformly at a constant rate of 140 kg/cm^2/min (as per ASTM C39/C39M or BS EN 12390-3), without shock, until the specimen failed.

4.1.4 *Failure mode*

Following the compressive strength tests, the failure modes of the concrete specimens were systematically examined in accordance with standard procedures such as EN 12390-3 and ASTM C39. The specimens exhibited both satisfactory and unsatisfactory failure patterns, reflecting variations in internal structure and material quality.

Satisfactory failure was characterized by a progressive and controlled cracking process, typically involving inclined shear cracks and axial splitting, indicative of relatively uniform stress distribution and adequate bonding between the cement matrix and aggregates. In these cases, failure occurred through a combined mechanism of aggregate fracture and paste cracking, suggesting a well-developed interfacial transition zone (ITZ) and effective load transfer within the material.

In contrast, unsatisfactory failure modes were marked by sudden and localized cracking, often accompanied by premature debonding at the aggregate–paste interface. Such behaviour is commonly associated with weak ITZ regions, increased porosity, and the presence of adhered mortar on recycled aggregates. Irregular crack propagation, brittle fracture, and in some cases surface spalling were also observed, indicating stress concentrations and non-uniform load distribution. These observations demonstrate that, beyond compressive strength values, the mode of failure provides critical insight into the structural integrity and homogeneity of recycled aggregate concrete.

Figure 20. Failure patterns observed in concrete specimens after compressive strength testing.
(a) Satisfactory failure characterized by inclined shear cracking and uniform crack distribution, indicating good bonding and homogeneous stress transfer.
(b) Unsatisfactory failure showing localized cracking and aggregate–paste debonding, associated with weak interfacial transition zones and non-uniform internal structure.

4.2 *TEST SETUP*

The program is consisted of 12 series of concrete with recycled aggregate which can be divided into two main groups regarding the aggregates:

Main recycled aggregate series	Modified broken concrete mixes
1.1-time crushed mixed debris	**8**.1-time crushed broken concrete + sand
2.1-time crushed mixed debris (workmanship)	**9**.1-time crushed broken concrete + lime
3.3 times crushed mixed debris	**10**.1-time crushed broken concrete + sand + lime
4.1-time crushed broken concrete	**11**.3 times crushed broken concrete + sand
5.3 times crushed broken concrete	**12**.1-time crushed broken concrete + coarse aggregate + sand
6.1-time crushed 50% mixed debris 50% broken concrete	
7.3 times crushed 50% mixed debris 50%broken concrete	

All the series of specimens are made using a mixer except one which is the 1-time crushed mixed debris. The reasons why it was carried out twice were Recycled aggregates, especially mixed debris, contain porous particles and adhered mortar, leading to very high-water absorption. As a result, In the first (workmanship) trial, extra water was deliberately added to achieve workable consistency.

In the second (mixer) trial, the mix relied on the initially assumed w/c ratio, resulting in poor workability and compaction difficulties.

By repeating the test under these two approaches, the aim was to:

- Quantify the practical water demand of recycled aggregates.
- Assess the effect of mixing method on compressive strength.
- Highlight the importance of water adjustment and workmanship in achieving reliable RAC performance.

4.2.1 *Crushing method*

All recycled aggregates were produced using a Crunchy portable jaw crusher. This machine is specifically designed for on-site recycling of demolition debris and is compact enough to be transported and operated in urban environments. The choice of a portable jaw crusher was made based on the unique constraints of the city of Genoa, where many buildings are in narrow alleys and historical streets that restrict access for large industrial crushing plants. On-site recycling is preferable to transporting debris long distances, which would be logistically difficult and environmentally costly. The portable crusher allows decentralized, small-scale processing, making recycling feasible directly at or near the demolition site. Thus, the Crunchy portable crusher provided a practical and context-specific solution for aggregate preparation in Genoa's urban environment.

Two levels of crushing were performed. For the 1-time crushing, the material was passed through the jaw crusher once, producing coarse recycled aggregates with some adhered mortar and irregular shapes. And for the 3-times crushing the material was recycled through the crusher three times, producing finer aggregates with better particle shape and gradation, and reducing the amount of attached mortar.

Figure 21. The mini jaw crusher crunchy crushing pieces of debris from the demolition of the buildings into smaller aggregates. The pictures are taken in the laboratory of university of genoa.

Figure 22. The pictures are directly taken from the official website www.crunchy.it

4.2.2 *THE AGGREGATES*

As it was discussed, the program is consisted of using 3 type of materials which are:

1. Mixed debris (MD)
2. Broken concrete (BC)
3. 50% MD-50% BC.

The characteristics and the expected behaviour of each material is indicated in the table below.

Aggregate Type	Composition	Density (Qualitative)	Water Absorption	Characteristics	Expected Behaviour in Concrete
Mixed Debris (MD)	Brick, clay, plaster, mortar, small concrete fragments	Low	Very High	Heterogeneous, porous, weak particles	Lower strength, high water demand, lightweight
Broken Concrete (BC)	Crushed old concrete (stone + adhered mortar)	Medium–High	Moderate	More homogeneous, stronger particles	Higher strength than MD, but less than natural aggregates
Mixed (50% MD + 50% BC)	Equal blend of MD and BC	Medium	High	Balance between weak clay and stronger concrete fragments	Intermediate performance, variable results

Table 7. Characteristics and expectations of different materials. The density and absorption values were determined experimentally and are expressed qualitatively here to highlight relative differences among aggregate types.

Figure 13. The pictures are taken in the laboratory of university of genoa. on the left it is the mixed debris, on the right is the broken concrete.

For each type of aggregates, six samples of density and water absorption are taken, and the average value is used in the mix design. The results of the density and water absorption of the aggregates is indicated in the tables below.

Density (kg/m^3)	M.D 1-time crushed	M.D 3 times crushed	B.C 1-time crushed	B.C 3 times crushed	50%-50% 1-time crushed	50%-50% 3 times crushed
Sample 1	1538	1879	1544	1965	1595	1861
Sample 2	1360	1764	1548	1994	1548	1821
Sample 3	1519	1735	1359	1970	1542	1800
Sample 4	1386	1861	1602	1950	1590	1820
Sample 5	1543	1677	1719	1994	1578	1817
Sample 6	1374	1604	1557	1732	1570	1755
Average	**1453**	**1753**	**1555**	**1934**	**1570**	**1812**

Water absorption (%)	M.D 1-time crushed	M.D 3 times crushed	B.C 1-time crushed	B.C 3 times crushed	50%-50% 1-time crushed	50%-50% 3 times crushed
Sample 1	15.6	14.2	12.0	13.0	17.5	16.4
Sample 2	19.5	17.1	15.1	13.6	14.1	17.8
Sample 3	20.0	19.0	11.4	13.7	15.5	16.7
Sample 4	19.7	16.3	9.8	13.8	15.1	16.4
Sample 5	22.7	17.0	13.8	12.3	16.7	15.2
Sample 6	19.1	17.3	13.6	13.9	18.2	16.1
Average	**19.4**	**16.8**	**12.6**	**13.4**	**16.2**	**16.5**

As it is evident from the results, broken concrete is denser than mixed debris comparatively. Especially when broken concrete is crushed three times. Thus, the water absorption percentage is lower in broken concrete compared to mixed debris. Whilst it can be noticed that the behaviour of 50% mixed debris and 50% broken concrete is intermediate. Eventually, our hypothesis was approved by the tests. However, to comparatively with previous studies, results were much higher. To justify, it is important to take into account that these aggregates are consisted of mixed materials and obviously each sample give different results as they're collected randomly.

4.2.3 *Cement*

The binder employed in this experimental program was Type II Portland cement. This cement is generally classified as a moderate sulphate-resistant cement, with a tricalcium aluminate content limited to below eight percent. The reduced C_3A fraction provides greater resistance to sulphate attack compared to ordinary Type I cement, while the overall heat of hydration is also lower, which contributes to the control of thermal cracking in larger concrete elements. From a mechanical standpoint, Type II cement develops strength at a rate comparable to Type I, but with a slightly more controlled hydration process that is advantageous in mixtures containing porous recycled aggregates.

The decision to use Type II cement in this study was primarily dictated by its availability in the local market, which made it the most practical option for continuous casting and testing. Beyond this practical aspect, the properties of Type II cement were beneficial for the experimental context, as the moderate heat generation and enhanced durability characteristics aligned well with the variable and absorptive nature of the recycled aggregates.

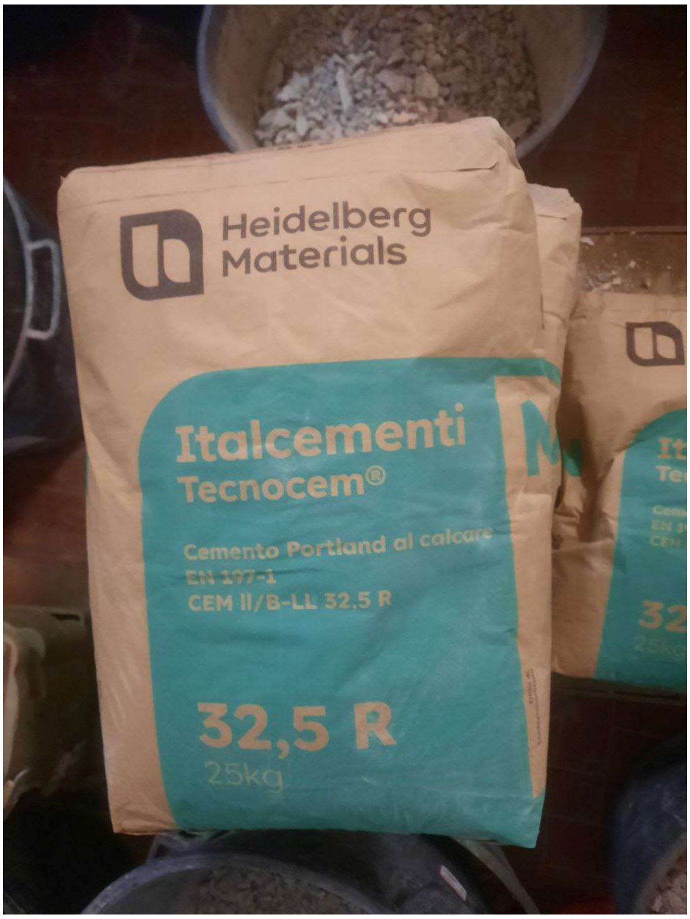


Figure 24.The Portland cement type II used in the program. The picture is taken in the laboratory of university of genoa.

4.2.4 *WATER*

Water was an essential parameter in this study, not only as a component of the cement hydration process but also as a critical factor influencing the workability of recycled aggregate concrete. The water–cement ratios were initially designed as 0.8, 0.7, and 0.6; however, due to the inherently high porosity and absorption capacity of the recycled aggregates, additional water had to be incorporated during mixing to achieve workable consistencies. This adjustment was necessary to ensure complete coating of the aggregate particles and to provide sufficient lubrication within the fresh mix.

The high absorption of both mixed debris and broken concrete aggregates altered the effective water–cement ratio, making it difficult to maintain the designed proportions with precision. As a result, the practical water demand of the recycled aggregate concretes exceeded that of conventional concretes produced with natural aggregates. This phenomenon not only affected the fresh properties but also had a direct influence on the compressive strength development, as part of the added water was consumed in saturating the aggregates rather than contributing to cement hydration. Consequently, water management became a critical aspect of the mix design and directly impacted the interpretation of the mechanical results.

Figure 25. During the preparation of the recycled aggregate concrete, water was added incrementally and carefully to the mixer to achieve the required workability. As shown in the figure, this step was performed manually to ensure better control of the effective water content. The adjustment was necessary because recycled aggregates, particularly mixed debris and broken concrete, exhibited high water absorption, which reduced the amount of free water available for cement hydration. By gradually introducing water, it was possible to compensate for the absorptive behaviour of the aggregates while avoiding an excessive increase in the effective water–cement ratio.

4.2.5 *ADDITIVE*

To improve the workability of recycled aggregate concrete and to partially compensate for the high-water absorption of the aggregates, a commercial admixture, identified as "*fluidificante*", was incorporated into the mixes. This additive belongs to the category of plasticizers, which act primarily by dispersing cement particles and reducing the internal friction of the fresh mix. Through this mechanism, the admixture enhances fluidity without requiring excessive additional water, thus helping to control the effective water–cement ratio.

In this study, the dosage of the admixture was fixed at 0.5% of the cement weight, following standard practice and the manufacturer's guidelines. Given that the cement content was 400 kg/m^3, this corresponded to an admixture dosage of 2 kg/m^3 of concrete. By adopting this proportional approach, consistency in the mixes was maintained across different series, despite the variability in aggregate properties.

The use of the thinner (fluidificante) allowed the recycled aggregate concretes to achieve workable fresh states suitable for casting, which would have otherwise been difficult to obtain due to the angularity and absorptive nature of the crushed materials. In addition to facilitating mixing and casting, the additive indirectly influenced the mechanical properties of the hardened concrete by reducing the risk of excessive water addition. While the admixture did not eliminate the need for added water in many mixes, it contributed to a better balance between workability and strength, supporting the overall objective of evaluating the feasibility of 100% recycled aggregate concrete.

It is important to note that no additional chemical admixtures, such as superplasticizers, accelerators, or retarders, were used. This ensured that the observed results could be attributed primarily to the properties of the recycled aggregates and the basic effect of the single additive applied.

4.2.6 *Lime*

As part of the experimental program, concrete mixtures incorporating recycled aggregates derived from crushed concrete were modified through the addition of lime prior to cement incorporation. The aim of this approach was to investigate the influence of lime on the mechanical performance of recycled aggregate concrete, with particular emphasis on its effect on mixture composition and microstructural development. The introduction of lime altered the overall fines content of the system, contributing to improved particle packing and a reduction in water demand. This modification is expected to promote the formation of a denser cementitious matrix and a more refined interfacial transition zone (ITZ) between the recycled aggregates and the surrounding paste.

From a chemical perspective, the presence of lime, primarily in the form of calcium hydroxide, may also influence the hydration kinetics of cementitious phases and modify the alkalinity of the system. These combined physical and chemical effects play a critical role in determining the resulting compressive strength and overall performance of the concrete and were therefore examined through comparative analysis with reference mixtures.

Chapter 5: The results

5.1 <u>*ONE-TIME CRUSHED BROKEN CONCRETE*</u>

In the first step, the granulometry of the aggregates is executed and brought in the tables below. As it is evident, a lack of fine aggregates has led to have the graph outside the criterions partially.

weight of sieves		Agg + sieve	Agg
25mm	1299	1317.5	18.5
19mm	1377	1416.5	39.5
12.5mm	1245	1836	591
9.5mm	1238	2325	1087
6.3mm	1183	2245.5	1062.5
4.75mm	1272	1772.5	500.5
2.36mm	1123	2221.5	1098.5
2mm	405	551	146
1.18mm	376	755	379
850µ	347.5	520.5	173
600µ	334	464.5	130.5
425µ	317	418	101
250µ	293	394.5	101.5
150µ	280	352	72
75µ	266.5	338	71.5
fondo	263	287.5	24.5
			5596.5
		Actual weight	5597
		missing	0.5

Coarse aggregate	3299

Table 11. One-time crushed broken concrete table of granulometry data in the unitary of grams.

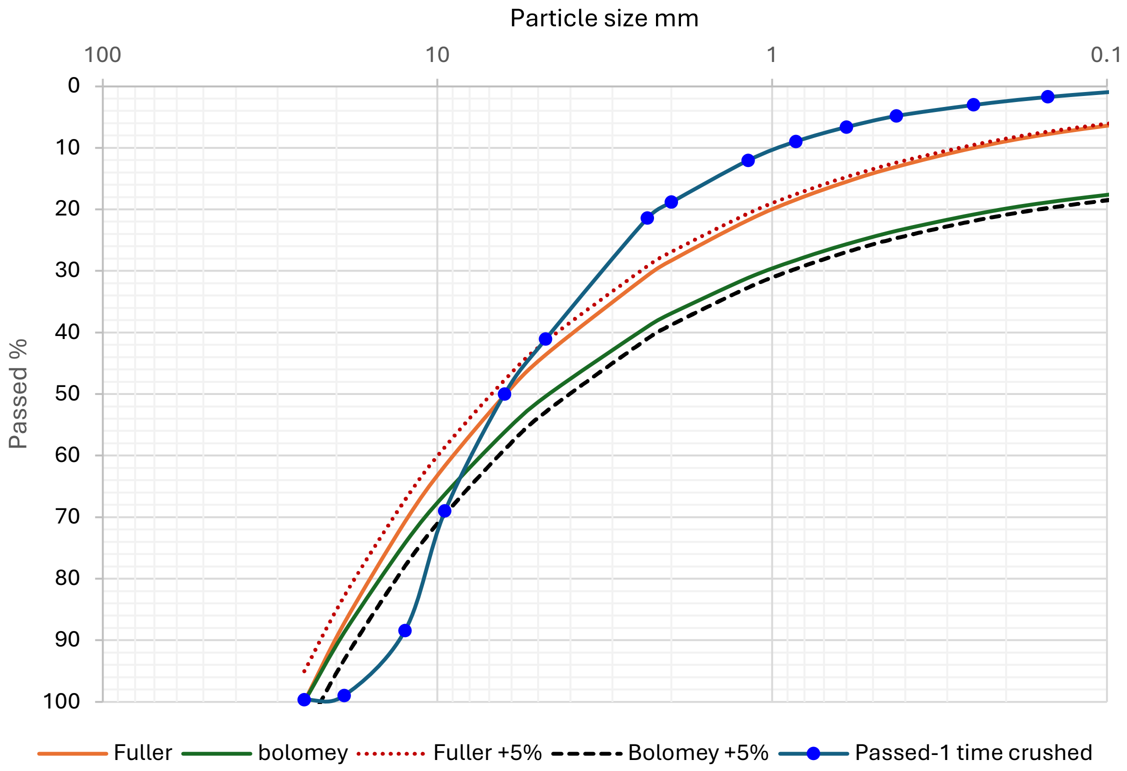


Figure 26. One-time crushed broken concrete graph of granulometry and the fuller and bolomey criterions.

Here are all the amounts of different materials to cast the concrete made of one-time crushed broken concrete aggregates. A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The water to cement ratio was considered 0.6 initially. however, due to high water absorption, to achieve the sufficient workability, more water was added during the mix. Eventually this proportion reached to 0.73.

INPUT		
Title	**Value**	**Unit**
Water volume	**291.2**	*kg/m^3*
Cement volume	400	*kg/m^3*
Aggregate	1555	*kg/m^3*
Width	0.15	*m*
Length	0.15	*m*
Height	0.15	*m*
Number of cubes	10	-
W/C	0.73	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2246.2**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**9.8**	*kg*
cement for all cubes	**13.5**	*kg*
agg. For all cubes	**52.5**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**75.9**	*kg*

Table 12. One-time crushed broken concrete table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14 ,28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	1 time crushed broken concrete					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	29-Apr-25					
Date of extraction	30-Apr-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.3145	1	134.8	1	5.99
Day 4	2	7.351	2	136.3	2	6.06
Day 7	1	7.234	1	214.2	1	9.52
Day 7	2	7.186	2	205.7	2	9.14
Day 14	1	7.373	1	333.4	1	14.82
Day 14	2	7.398	2	322.4	2	14.33
Day 28	1	7.33	1	426.5	1	18.95
Day 28	2	7.3025	2	437	2	19.43
Day 90	1	7.361	1	641.1	1	28.48
Day 90	2	7.3445	2	646.9	2	28.75

Table 13. The results of one-time crushed broken concrete specimens after tests.

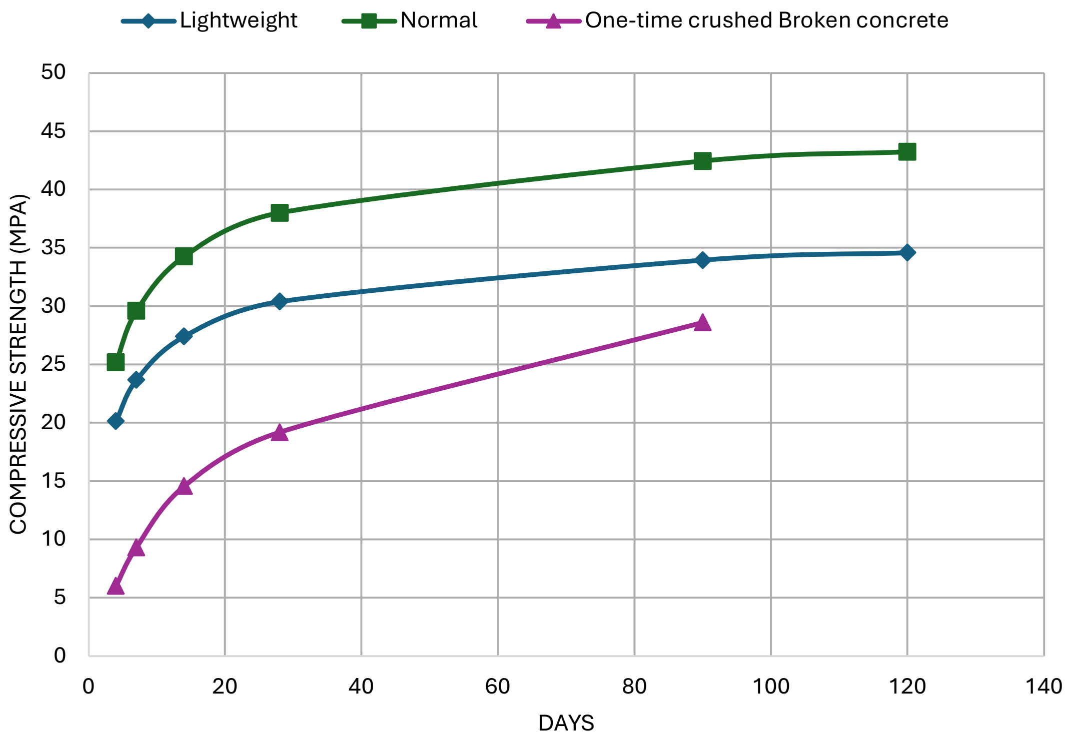


Figure 27. The results of compressive strength tests with respect to normal and lightweight concrete.

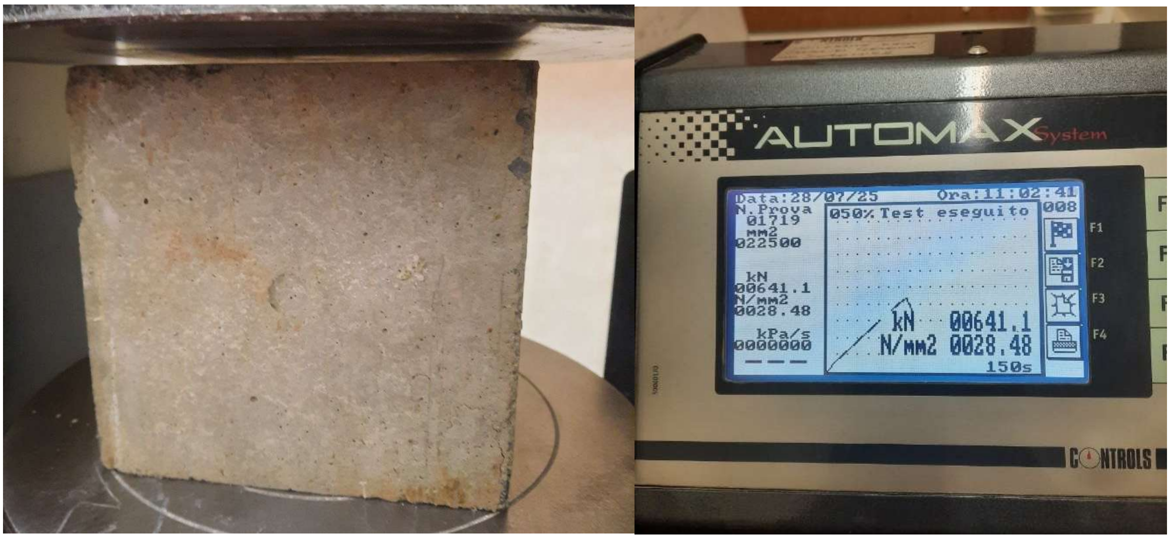


Figure 28. The failure crack pattern of the 90-day specimen.

5.2 *THREE-TIMES CRUSHED BROKEN CONCRETE*

Crushing the same material for the third time leads to obtain denser aggregates as expected. The granulometry test is executed to study the particle size distribution and brought in the table below.

3 times crush broken concrete			
weight of sieves		Agg + sieve	Agg
25mm	1299	1299	0
19mm	1377	1387	10
12.5mm	1245	1382.5	137.5
9.5mm	1238	2059	821
6.3mm	1183	2171.5	988.5
4.75mm	1272	1667.5	395.5
2.36mm	1123	2168	1047
2mm	405	556.5	151.5
1.18mm	376	748.5	372.5
850µ	347.5	543	195.5
600µ	334	494.5	160.5
425µ	316.5	490	173.5
250µ	293	505	212
150µ	279.5	410	130.5
75µ	266.5	422.5	156
Fondo	263	302	39
			4990.5
		Actual weight	4997
		Missing	6.5

Coarse aggregate	2352.5

Table 14. Three times crushed broken concrete table of granulometry in unitary of grams

Comparing the results of one time crushed and three times crushed, it can be understood that three times crushed has almost one kilogram less coarse aggregates with respect to one-time crushed. The graph of granulometry is shown in the figure below.

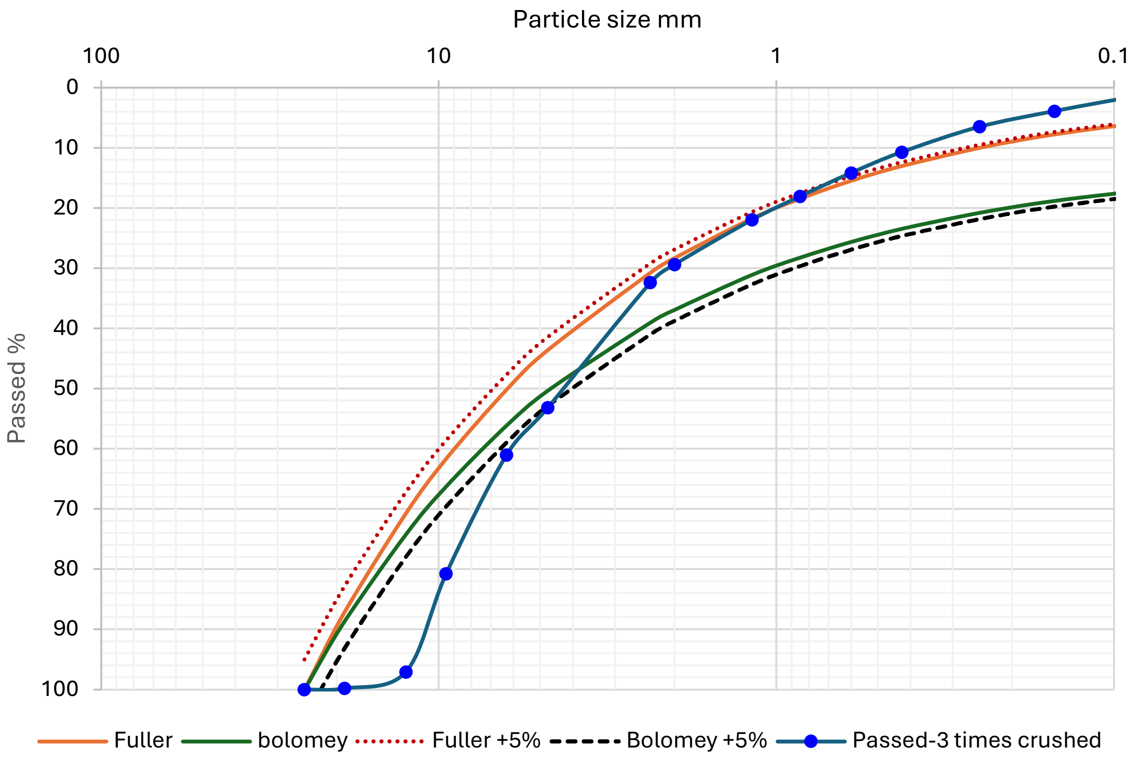


Figure 29. Three times crushed broken concrete graph of granulometry and the fuller and bolomey criterions.

Here are all the amounts of different materials to cast the concrete made of one-time crushed broken concrete aggregates. A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The water to cement ratio was considered 0.6 initially. however, due to high water absorption, to achieve the sufficient workability, more water was added during the mix. Eventually this proportion reached to 0.84.

INPUT		
Title	**Value**	**Unit**
Water volume	336	*kg/m^3*
Cement volume	400	*kg/m^3*
Aggregate	1934	*kg/m^3*
Width	0.15	*m*
Length	0.15	*m*
Height	0.15	*m*
Number of cubes	10	-
W/C	0.84	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2670**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**11.34**	*kg*
cement for all cubes	**13.5**	*kg*
agg. For all cubes	**65.3**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**90.2**	*kg*

Table 15. Three times crushed broken concrete table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14 ,28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	3 times crushed broken concrete					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	30-Apr-25					
Date of extraction	02-May-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.1985	1	152.7	1	6.79
Day 4	2	7.256	2	165.9	2	7.37
Day 7	1	7.001	1	188.2	1	8.36
Day 7	2	7.187	2	198.7	2	8.83
Day 14	1	7.0225	1	264	1	11.73
Day 14	2	7.1615	2	270.3	2	12.01
Day 28	1	7.257	1	367.3	1	16.32
Day 28	2	7.13	2	341.7	2	15.18
Day 90	1	7.2605	1	534	1	23.73
Day 90	2	7.166	2	488.3	2	21.7

Table 16. The results of Three times crushed broken concrete specimens after tests.

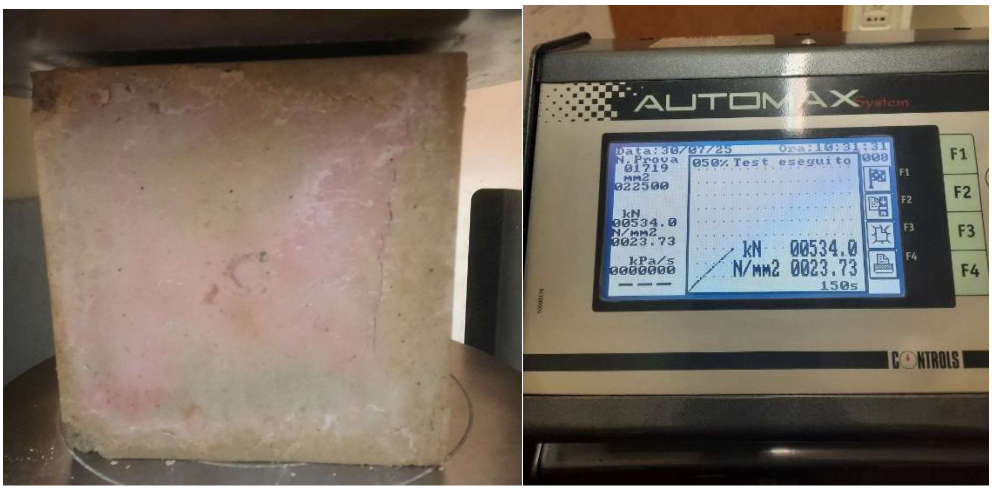


Figure 20.The failure crack pattern of the 90-day specimen.

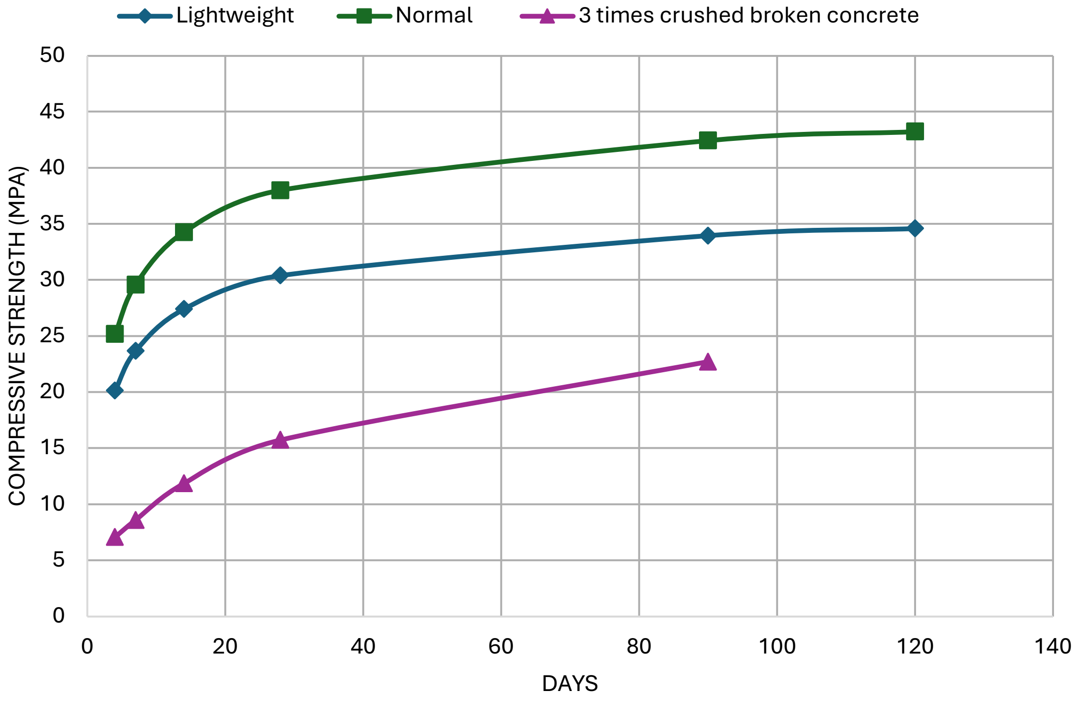


Figure 31. The results of compressive strength tests with respect to normal and lightweight concrete.

Despite of expectations, although finer aggregates are denser, their results were neither satisfactory nor better than one-time crushed broken concrete.

5.3 ONE-TIME CRUSHED 100% MIXED DEBRIS

In this study, concrete incorporating one-time crushed mixed debris as aggregates was prepared using two different mixing techniques: mechanical mixing and manual mixing. The objective of adopting these two methods was to simulate variations in workmanship conditions typically encountered in practical construction scenarios.

Mechanical mixing ensures a more uniform and controlled mixing process, representing ideal or laboratory conditions. In contrast, manual mixing reflects on-site practices where workmanship, operator skill, and consistency can significantly influence the quality of concrete.

By comparing these two methods, the study aims to evaluate the sensitivity of recycled aggregate concrete to mixing quality and to assess its performance under both controlled and practical conditions. This approach provides insight into the robustness and field applicability of the material, especially in contexts where advanced equipment may not be available.

To begin, the granulometry test was executed and the results are brought to in the table below.

1-time crushed 100%mixed debris			
weight of sieves		Agg + sieve	Agg
25mm	1296.4	1375.2	78.8
19mm	1375.6	1608.2	232.6
12.5mm	1242.4	2290.6	1048.2
9.5mm	1236.2	2541.4	1305.2
6.3mm	1181.6	2093	911.4
4.75mm	1269.6	1614	344.4
2.36mm	1120.6	1757	636.4
2mm	404	486.6	82.6
1.18mm	375.2	610.2	235
850µ	335.8	476.4	140.6
600µ	330	500	170
425µ	315.8	678	362.2
250µ	281.4	364.4	83
150µ	279.4	326.4	47
75µ	266	279.6	13.6
Fondo	317.2	321.4	4.2
			5695.2
	Actual weight		5700
	Missing		4.8

Coarse aggregate	3920.6

Table 17. One-time crushed 100% mixed debris table of granulometry data in the unitary of grams.

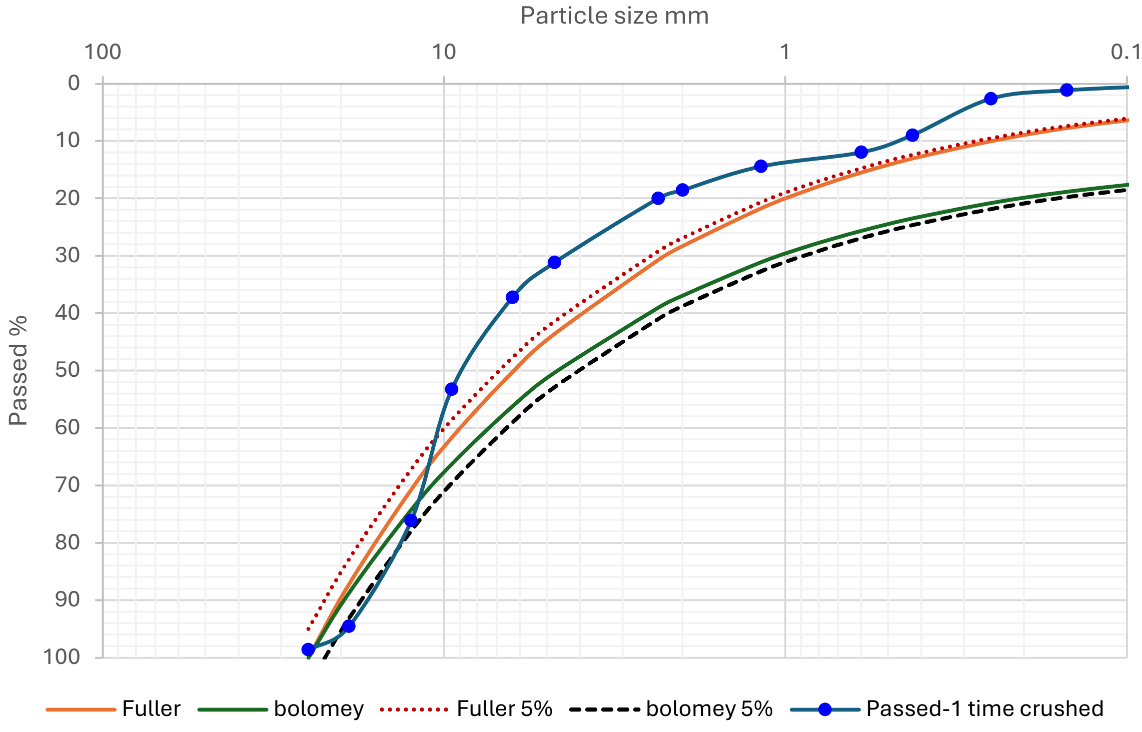


Figure 32. One-time crushed 100% mixed debris graph of granulometry and the fuller and bolomey criterions.

5.3.1 *MANUAL MIXING (WORKMANSHIP)*

A total of ten concrete cubes were expected, but a total of eight out of ten cubes could be extracted only. The water to cement ratio was considered 0.8 initially, however, due to high water absorption, more water was added during the mix. Eventually this proportion reached to 0.86. Here are all the amounts of different materials used in the concrete shown in the table below.

INPUT			OUTPUT		
Title	Value	Unit	title	value	unit
Water	344	kg/m^3	volume of 1 cube	0.003375	m^3
Cement	400	kg/m^3	total volume	2197	kg/m3
Aggregate	1453	kg/m^3	Total cube volume	0.03375	kg/m3
Width of cube	0.15	m	Water for 10 cubes	11.61	kg
Length of cube	0.15	m	cement for 10 cubes	13.5	kg
Height of cube	0.15	m	agg. For 10 cubes	49.0	kg
Number of cubes	10	-	Additive	0.0675	kg
W/C	0.86	-	total 10 cube weight	74.2	kg

Table 18. One-time crushed 100% mixed debris table of materials using manual mixing.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 7 ,14 ,28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	1 time crushed 100% mixed debris					
Number of specimens	8					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	01-Apr-25					
Date of extraction	02-Apr-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1		1		1	
Day 4	2		2		2	
Day 7	1	6.672	1	164.5	1	7.31
Day 7	2	6.74	2	177.3	2	7.88
Day 14	1	6.6745	1	234.9	1	10.44
Day 14	2	6.719	2	247.05	2	10.98
Day 28	1	6.771	1	284.8	1	12.66
Day 28	2	6.839	2	311.4	2	13.84
Day 90	1	6.832	1	430.3	1	19.12
Day 90	2	6.7325	2	375.6	2	16.69

Table 19. The results of one-time crushed 100% mixed debris (workmanship) specimens after tests.

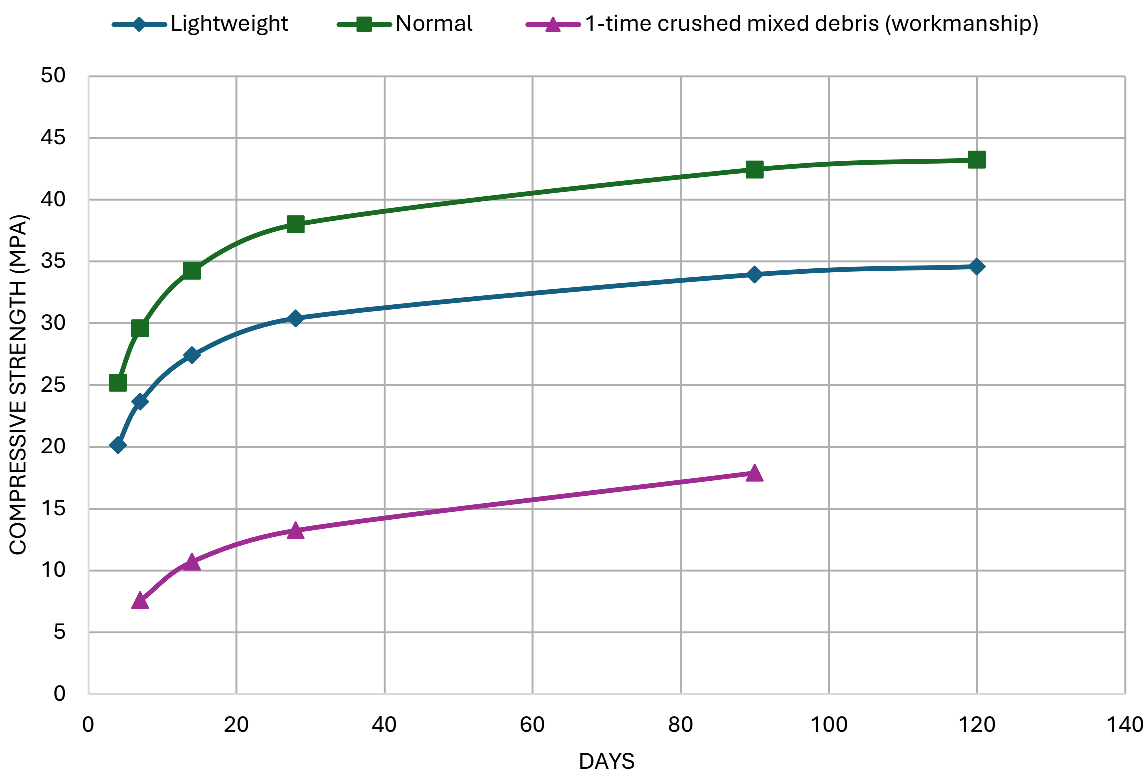


Figure 33. The results of compressive strength tests with respect to normal and lightweight concrete.

5.3.2 *MECHANICAL MIXING*

Using the mixer, led to use less water. Therefore, the water to cement ratio remained 0.8 as expected. However, instead of ten cubes, only 7 cubes were yielded. This reduction in yield which happened in both cases, can be attributed to the characteristics of the recycled aggregates and the mixing process.

Recycled aggregates derived from crushed mixed debris tend to have higher water absorption and irregular particle shapes, leading to increased void content and reduced workability. As a result, a larger portion of the cement paste is required to fill internal voids, effectively decreasing the available volume of concrete for casting.

Additionally, material losses during mixing and handling, particularly in manual mixing, contributed to the reduced yield. The discrepancy between theoretical and actual yield highlights the influence of aggregate properties and workmanship on concrete production, especially when using recycled materials.

In the table below, the materials used in the mechanical mixing case are shown.

INPUT			OUTPUT		
Title	**Value**	**Unit**	**title**	**value**	**unit**
Water	320	*kg/m^3*	**volume of 1 cube**	0.003375	*m^3*
Cement	400	*kg/m^3*	**total volume**	2173	*kg/m3*
Aggregate	1453	*kg/m^3*	**Total cube volume**	0.03375	*kg/m3*
Width of cube	0.15	*m*	**Water for all cubes**	10.8	*kg*
Length of cube	0.15	*m*	**cement for all cubes**	13.5	*kg*
Height of cube	0.15	*m*	**agg. For all cubes**	49.0	*kg*
Number of cubes	10	-	**Additive**	0.0675	*kg*
W/C	0.80	-	**total cube weight**	73.4	*kg*

Table 20. One-time crushed 100% mixed debris table of materials using mechanical mixing.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed for each age of 7 ,14 ,28 and 120 days. Here is the table that shows the compressive strength of each cube in MPa.

	1 time crushed 100% mixed debris (mixer)					
Number of specimens	7					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	29-May-25					
Date of extraction	30-May-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1		1		1	
Day 4	2		2		2	
Day 7	1	7.01	1	406.8	1	18.07
Day 7	2	7.193	2	403	2	17.91
Day 14	1	7.122	1	444.7	1	19.76
Day 14	2	-	2	-	2	-
Day 28	1	7.057	1	528.5	1	23.49
Day 28	2	7.23	2	534.2	2	23.74
Day 120	1	7.016	1	641	1	28.49
Day 120	2	7.02	2	615.8	2	27.37

Table 21. The results of one-time crushed 100% mixed debris (mechanical mixing) specimens after tests.

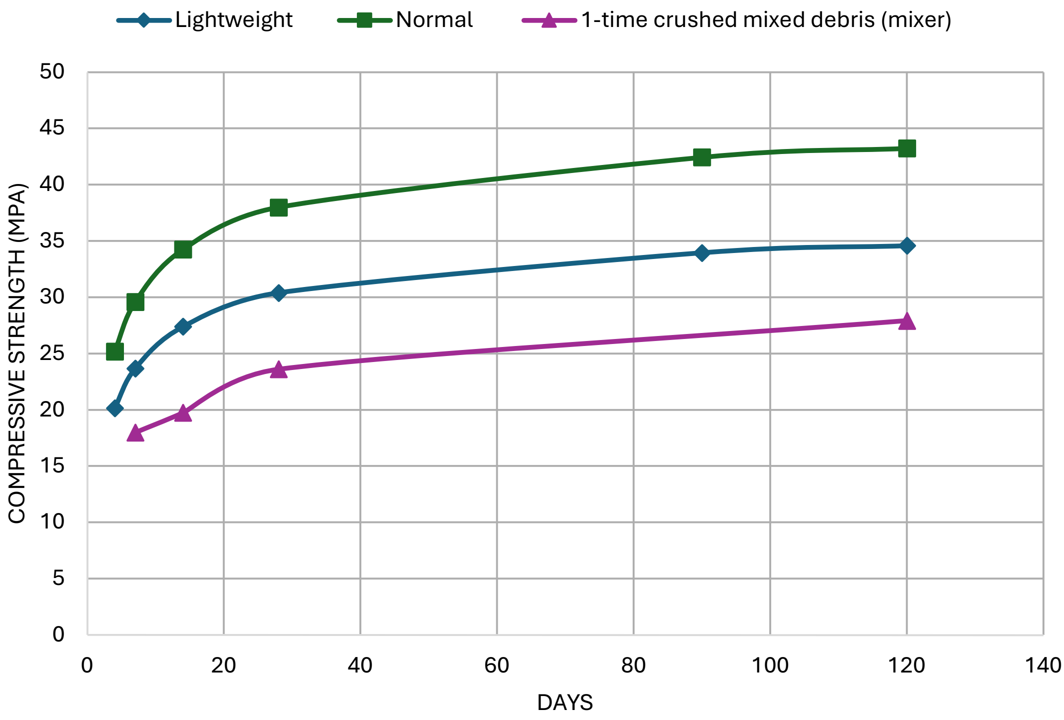


Figure 34. The results of compressive strength tests with respect to normal and lightweight concrete.

The observed failure modes were consistent with the mechanical performance trends obtained from compressive strength measurements.

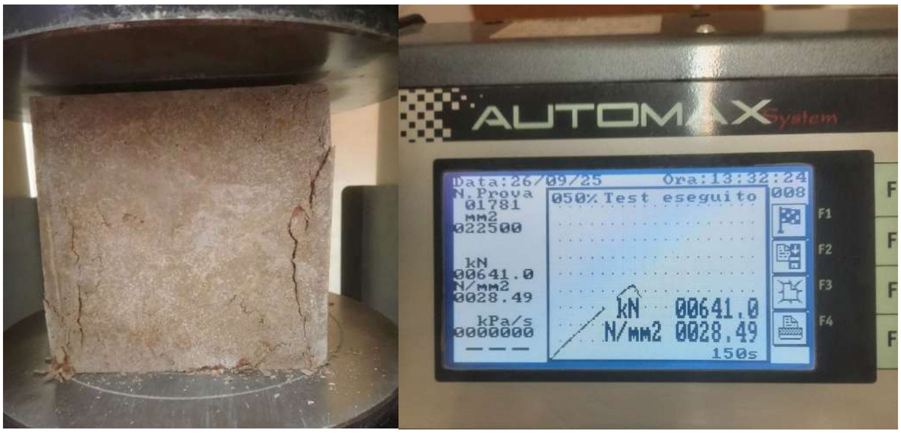


Figure 35. The failure crack pattern of the 120-day specimen.

5.4 ***THREE-TIMES CRUSHED 100% MIXED DEBRIS***

After crushing the mixed debris for three times, the granulometry test is executed and the results are brought in the table below.

3 times crush mixed debris			
weight of sieves		**Agg + sieve**	**Agg**
25mm	1296.4	1296.4	0
19mm	1375.6	1375.6	0
12.5mm	1242.4	1418	175.6
9.5mm	1236.2	2126	889.8
6.3mm	1181.6	2228.4	1046.8
4.75mm	1269.6	1708.8	439.2
2.36mm	1120.6	2145.6	1025
2mm	404	575.4	171.4
1.18mm	375.2	809.8	434.6
850µ	348	510	162
600µ	329.8	783.2	453.4
425µ	315.8	529.4	213.6
250µ	281.4	609	327.6
150µ	279.4	439.2	159.8
75µ	266	460.2	194.2
Fondo	317.2	392.2	75
			5768
	Actual weight		5781.2
		Missing	13.2

Coarse aggregate	2551.4

Table 22. Three times crushed 100% mixed debris table of granulometry data in the unitary of grams.

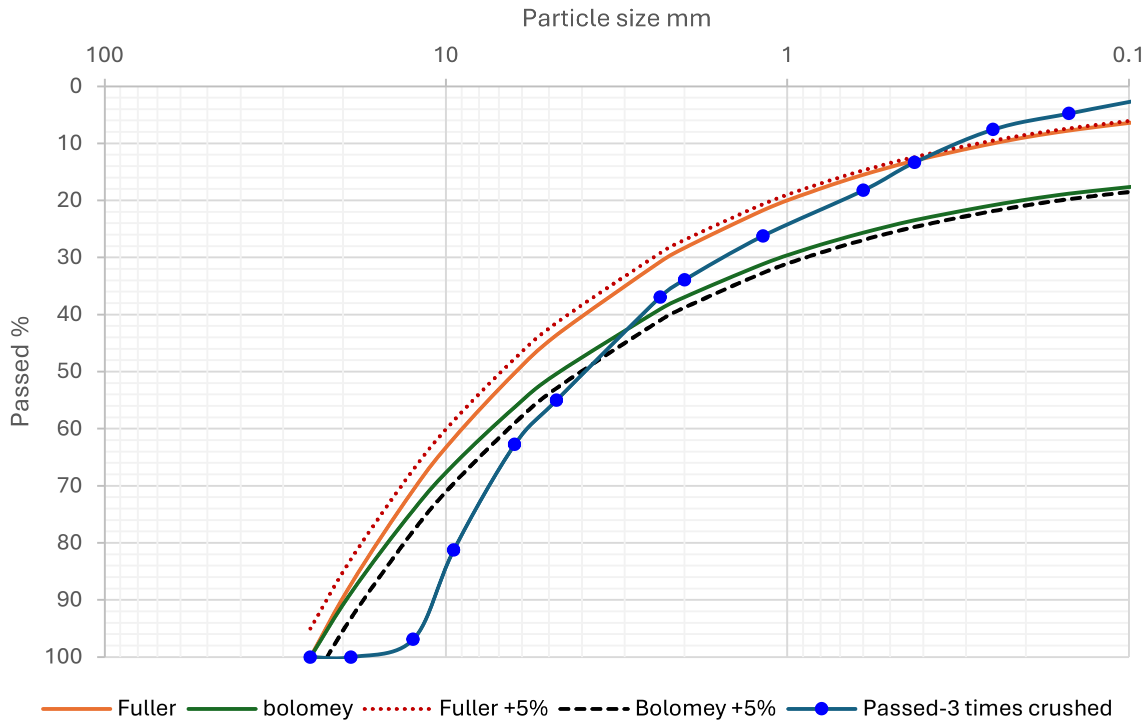


Figure 36. Three times crushed 100% mixed debris graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The water to cement ratio was considered 0.8 initially, however, due to high water absorption, more water was added during the mix. Eventually this proportion reached to 0.86. Here are all the amounts of different materials used in the concrete shown in the table below.

INPUT			OUTPUT		
Title	Value	Unit	title	value	unit
Water volume	344	kg/m^3	volume of 1 cube	0.003375	m^3
Cement volume	400	kg/m^3	total volume	2497	kg/m3
Aggregate	1753	kg/m^3	Total cube volume	0.03375	kg/m3
Width	0.15	m	Water for all cubes	11.61	kg
Length	0.15	m	cement for all cubes	13.5	kg
Height	0.15	m	agg. For all cubes	59.2	kg
Number of cubes	10	-	Additive	0.0675	kg
W/C	0.86	-	total cube weight	84.3	kg

Table 23. Three times crushed 100% mixed debris table of materials used.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14 ,28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa. It was observed that the workability enhances considerably as the aggregates are crushed two times more.

	3 times crushed mixed debris					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	22-Apr-25					
Date of extraction	24-Apr-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.024	1	195.6	1	8.69
Day 4	2	6.966	2	189.6	2	8.43
Day 7	1	7.078	1	194.8	1	8.66
Day 7	2	7.126	2	199.1	2	8.85
Day 14	1	7.136	1	304.2	1	13.52
Day 14	2	7.1675	2	304.8	2	13.55
Day 28	1	7.1365	1	383.9	1	17.06
Day 28	2	7.111	2	382.7	2	17.01
Day 90	1	7.164	1	540.7	1	24.03
Day 90	2	7.038	2	528.3	2	23.48

Table 24. The results of three times crushed 100% mixed debris specimens after tests.

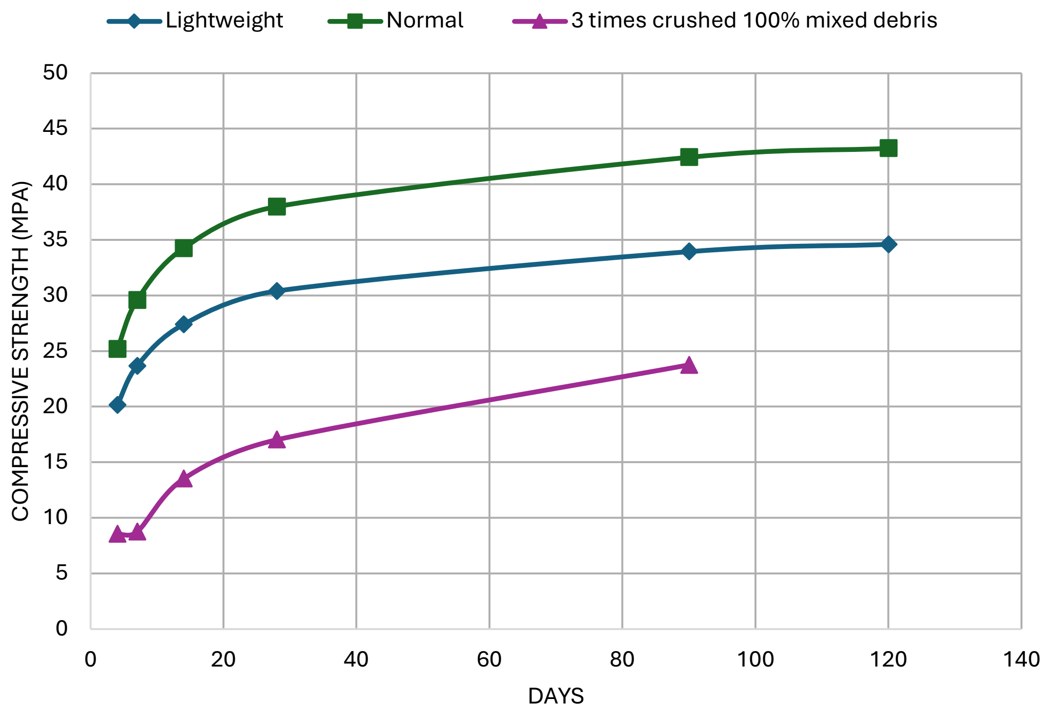


Figure 37. The results of compressive strength tests with respect to normal and lightweight concrete.

5.5 *ONE-TIME CRUSHED 50% BROKEN CONCRETE 50% MIXED DEBRIS*

To study the behaviour of the materials combined, the granulometry of the combination of broken concrete and mixed debris is executed. The table below shows the data obtained.

1 time crush 50%50%			
weight of sieves		Agg + sieve	Agg
25mm	1296.4	1308.4	12
19mm	1375.6	1506.2	130.6
12.5mm	1242.4	1936	693.6
9.5mm	1236.2	2241	1004.8
6.3mm	1181.6	1998.6	817
4.75mm	1269.6	1634.4	364.8
2.36mm	1120.6	1936.4	815.8
2mm	404	517	113
1.18mm	375.2	721.6	346.4
850µ	335.8	541.6	205.8
600µ	330	519	189
425µ	315.8	562.8	247
250µ	281.4	516.6	235.2
150µ	279.4	424.2	144.8
75µ	266	380.6	114.6
Fondo	317.2	368.6	51.4
			5485.8
	Actual weight		5498
	Missing		12.2

Coarse aggregate	3022.8

Table 25. One-time crushed 50% Broken concrete 50% mixed debris table of granulometry data in the unitary of grams.

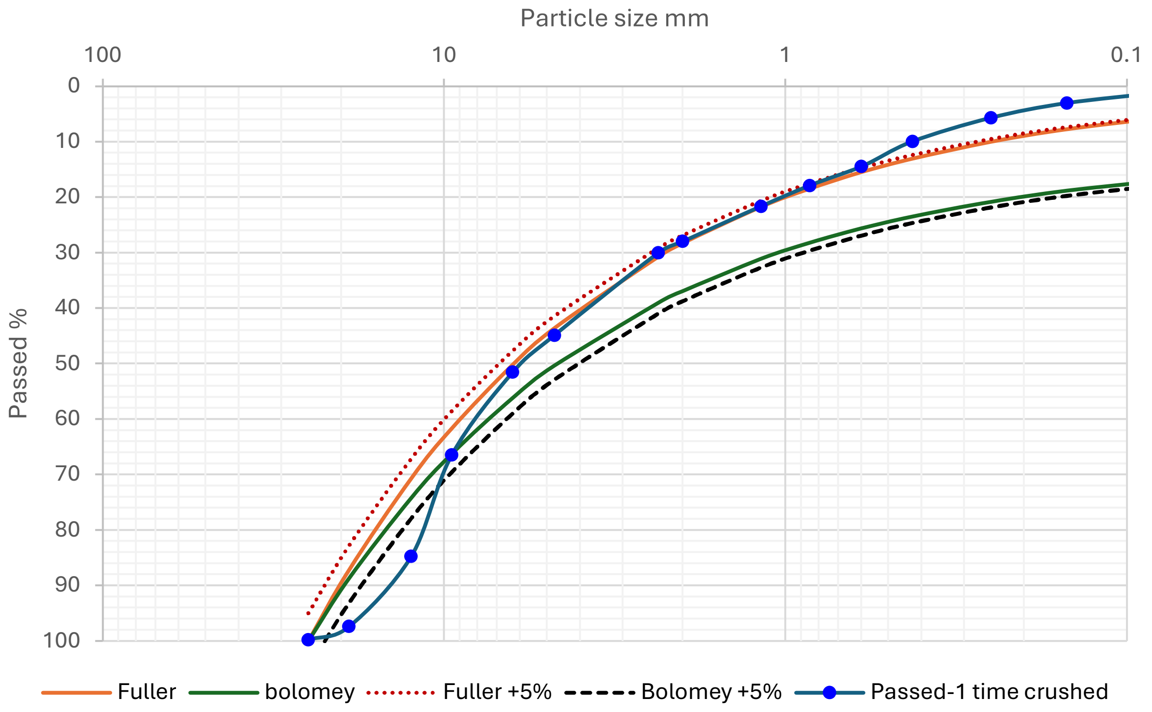


Figure 38. One-time crushed 50% Broken concrete 50% mixed debris graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The water to cement ratio was considered 0.7 initially, however, due to high water absorption, more water was added during the mix. Eventually this proportion reached to 0.77. Here are all the amounts of different materials used in the concrete shown in the table below.

INPUT			OUTPUT		
Title	Value	Unit	title	value	unit
Water volume	308	kg/m^3	volume of 1 cube	0.003375	m^3
Cement volume	400	kg/m^3	total volume	2278	kg/m3
Aggregate	1570	kg/m^3	Total cube volume	0.03375	kg/m3
Width	0.15	m	Water for 10 cubes	10.4	kg
Length	0.15	m	cement for 10 cubes	13.5	kg
Height	0.15	m	agg. For 10 cubes	53.0	kg
Number of cubes	10	-	Additive	0.0675	kg
W/C	0.77	-	total 10 cube weight	77.0	kg

Table 26. One-time crushed 50% Broken concrete 50% mixed debris table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14 ,28 and 120 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	1 time crushed 50% mixed debris 50% broken concrete					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	12-May-25					
Date of extraction	14-May-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.253	1	149.1	1	6.63
Day 4	2	7.3175	2	153	2	6.8
Day 7	1	7.245	1	214	1	9.51
Day 7	2	7.21	2	219	2	9.77
Day 14	1	7.1975	1	333	1	14.79
Day 14	2	7.2975	2	329.1	2	14.63
Day 28	1	7.264	1	418.6	1	18.6
Day 28	2	7.259	2	409	2	18.18
Day 120	1	7.2545	1	587.6	1	26.11
Day 120	2	7.3415	2	604.6	2	26.87

Table 27. The results of one-time crushed 50% Broken concrete 50% mixed debris specimens after tests.

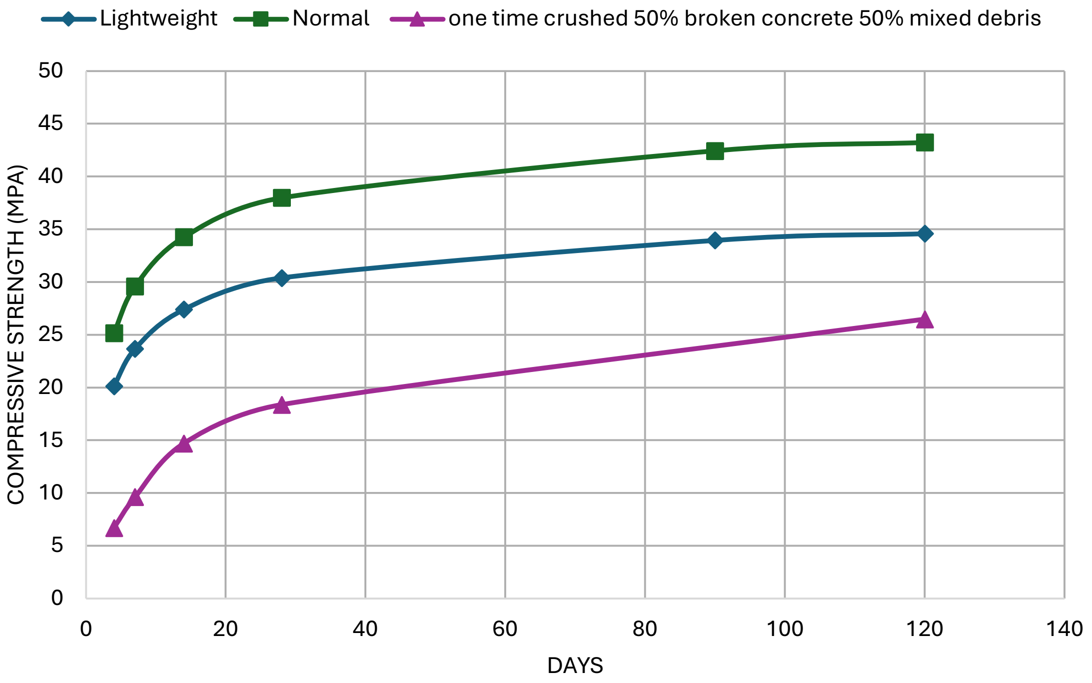


Figure 39. The results of compressive strength tests with respect to normal and lightweight concrete.

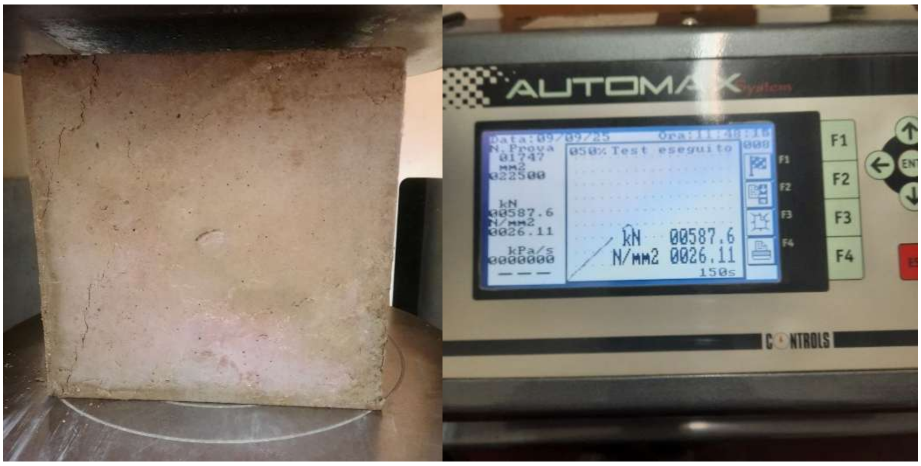


Figure 40. The failure crack pattern of the 120-day specimen.

5.6 *THREE-TIMES CRUSHED 50% BROKEN CONCRETE 50% MIXED DEBRIS*

The same procedure is carried out for three times crushed 50% broken concrete 50% mixed debris. The materials are completely combined and then the granulometry is executed.

3 times crush 50/50			
weight of sieves		Agg + sieve	Agg
25mm	1296.4	1296.4	0
19mm	1375.6	1375.6	0
12.5mm	1242.4	1413.4	171
9.5mm	1236.2	1926.2	690
6.3mm	1181.6	2069.4	887.8
4.75mm	1269.6	1623.6	354
2.36mm	1120.6	2091.4	970.8
2mm	404	583.2	179.2
1.18mm	375.2	841.4	466.2
850µ	348	632.6	284.6
600µ	329.8	616.8	287
425µ	315.8	753	437.2
250µ	281.4	731.6	450.2
150µ	279.4	542.4	263
75µ	266	410.2	144.2
Fondo	317.2	370	52.8
			5638
	Actual weight		5640.7
	Missing		2.7

Coarse aggregate	2102.8

Table 28. 3-times crushed 50% Broken concrete 50% mixed debris table of granulometry data in unit of grams.

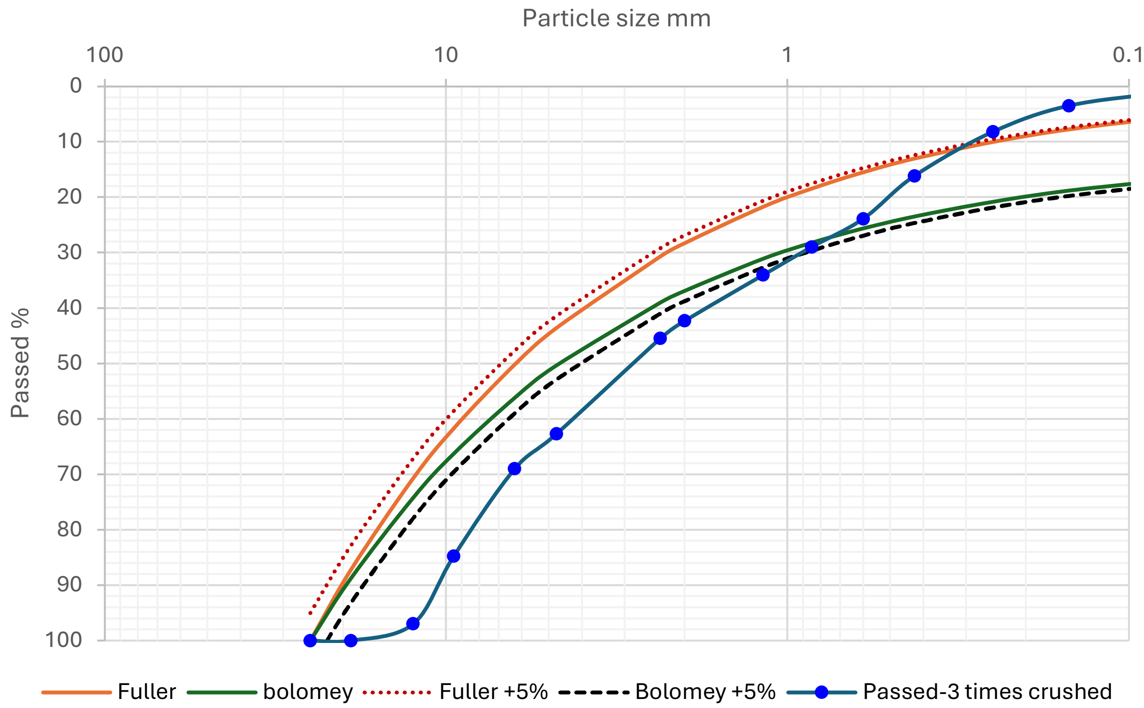


Figure 41. Three-times crushed 50% Broken concrete 50% mixed debris graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The water to cement ratio was considered 0.7 initially, however, due to high water absorption, more water was added during the mix. Eventually this proportion reached to 0.84. Here are all the amounts of different materials used in the concrete shown in the table below.

INPUT		
Title	**Value**	**Unit**
Water volume	**336**	*kg/m^3*
Cement volume	400	*kg/m^3*
Aggregate	1812	*kg/m^3*
Width	0.15	*m*
Length	0.15	*m*
Height	0.15	*m*
Number of cubes	10	-
W/C	0.84	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2548**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**11.3**	*kg*
cement for all cubes	**13.5**	*kg*
agg. For all cubes	**61.2**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**86.1**	*kg*

Table 29. Three-times crushed 50% Broken concrete 50% mixed debris table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14 ,28 and 120 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	3 times crushed 50% mixed debris 50% broken concrete					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	26-May-25					
Date of extraction	27-May-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.259	1	147.2	1	6.54
Day 4	2	7.266	2	151	2	6.71
Day 7	1	7.2755	1	241.9	1	10.75
Day 7	2	7.216	2	241.7	2	10.74
Day 14	1	7.222	1	332.4	1	14.77
Day 14	2	7.2615	2	338.5	2	15.05
Day 28	1	7.2955	1	455.2	1	20.23
Day 28	2	7.1715	2	451.8	2	20.08
Day 120	1	7.33	1	619.4	1	27.53
Day 120	2	7.328	2	625.5	2	27.8

Table 30. The results of three-times crushed 50% Broken concrete 50% mixed debris specimens after tests.

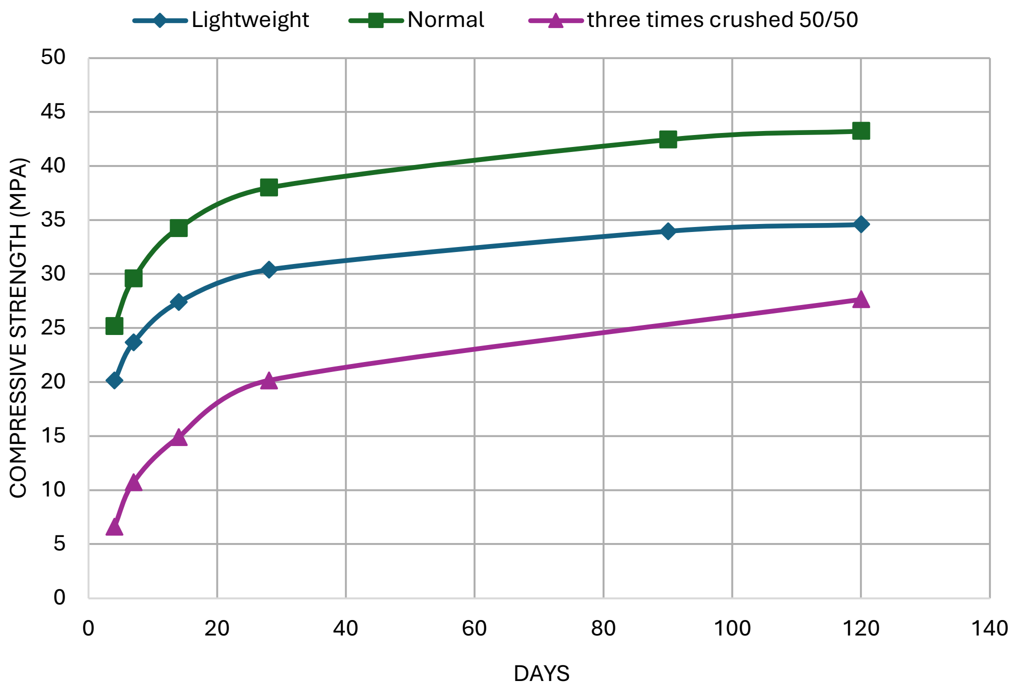


Figure 42. The results of compressive strength tests with respect to normal and lightweight concrete.

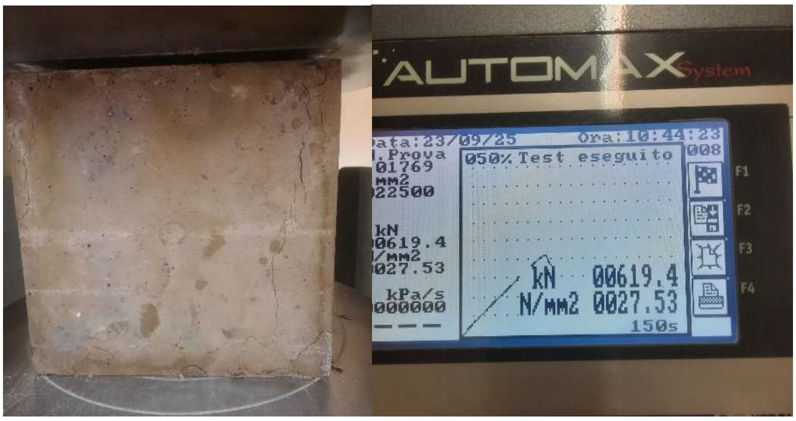


Figure 44. The failure crack pattern of the 120-day specimen.

5.7 *ONE-TIME CRUSHED BROKEN CONCRETE + SAND*

Additional sand was incorporated into the aggregate mix for optimizing the granulometry. Sand gives more paste to the concrete and fills the voids. Therefore, it is expected to have more compressive strength. At first the granulometry is executed.

1-time crushed concrete + Sand			
weight of sieves		**Agg 1+ sieve**	**Agg 1**
25mm	1298.5	1430	131.5
19mm	1378	1439	61
12.5mm	1245	2052	807
9.5mm	1238.5	2113.5	875
6.3mm	1183	1780.5	597.5
4.75mm	1272.5	1504	231.5
2.36mm	1123	1658.5	535.5
2mm	404.5	484.5	80
1.18mm	375.5	588	212.5
850µ	347	452.5	105.5
600µ	334.5	480.5	146
425µ	318	746	428
250µ	294	894	600
150µ	280	489	209
75µ	266.5	352	85.5
Fondo	262.5	302.5	40
			5145.5
	Actual weight		5165
	Missing		19.5

Coarse aggregates	2703.5

Table 31. One-time crushed Broken concrete + Sand table of granulometry data in the unitary of grams.

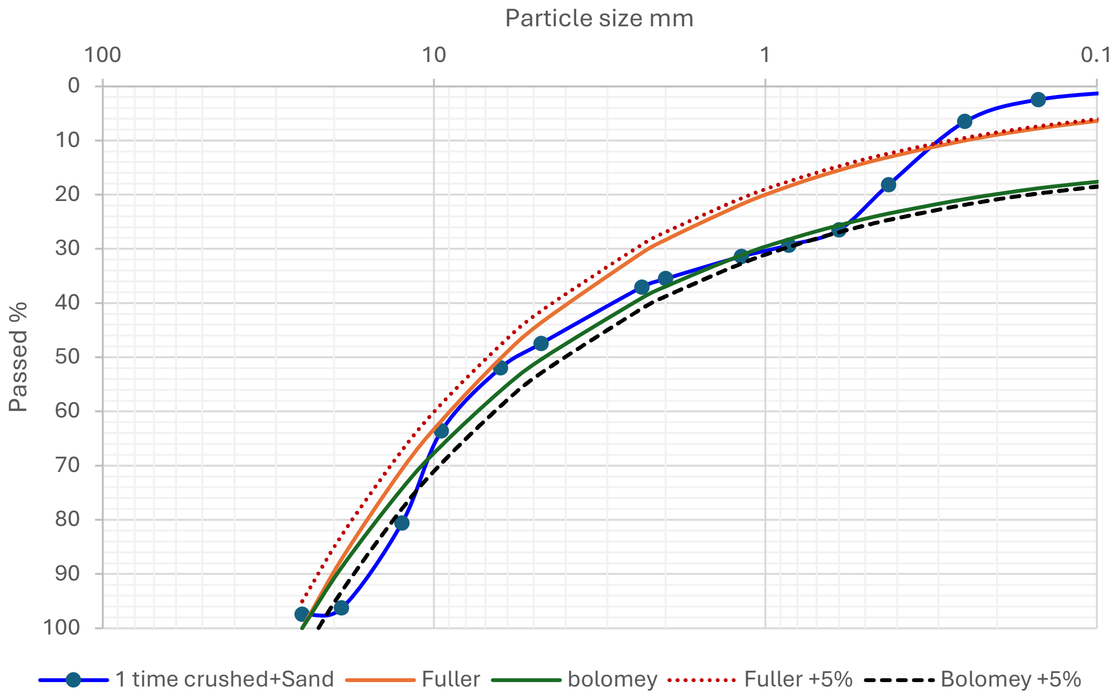


Figure 44. One-time crushed Broken concrete + Sand graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, but this requirement was not satisfactorily met and 9 cubes were extracted. The amount of sand was calculated in such way that each cube demanded 1 kilogram of sand. The water to cement ratio was considered 0.6 and this proportion remained constant, to have the desired workability. Therefore, no water was added during the mix. Here are all the amounts of different materials used in the concrete shown in the table below.

INPUT		
Title	**Value**	**Unit**
Water	**240**	*kg/m^3*
Cement	400	*kg/m^3*
Aggregate	1555	*kg/m^3*
Width of cube	0.15	*m*
Length of cube	0.15	*m*
Height of cube	0.15	*m*
Number of cubes	10	-
W/C	0.60	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2195**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**8.1**	*kg*
cement for all cubes	**13.5**	*kg*
Sand	**10**	*kg*
agg. For all cubes	**42.5**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**74.1**	*kg*

Table 32. One-time crushed Broken concrete + Sand table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 7 ,14 ,28 and 90 days there are two cubes to be broken. Only age day 4 has 1 sample. Here is the table that shows the compressive strength of each cube in MPa.

	1-time crushed broken concrete +Sand					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	10-Jun-25					
Date of extraction	11-Jun-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.621	1	552.9	1	24.57
Day 4	2	-	2	-	2	-
Day 7	1	7.679	1	655.7	1	29.14
Day 7	2	7.6635	2	643.6	2	28.6
Day 14	1	7.702	1	693.9	1	30.83
Day 14	2	7.7515	2	658.7	2	29.27
Day 28	1	7.7535	1	717.7	1	31.89
Day 28	2	7.6665	2	721.1	2	32.05
Day 90	1	7.6395	1	766	1	34.04
Day 90	2	7.694	2	762.9	2	33.91

Table 33. The results of One-time crushed Broken concrete + Sand specimens after tests.

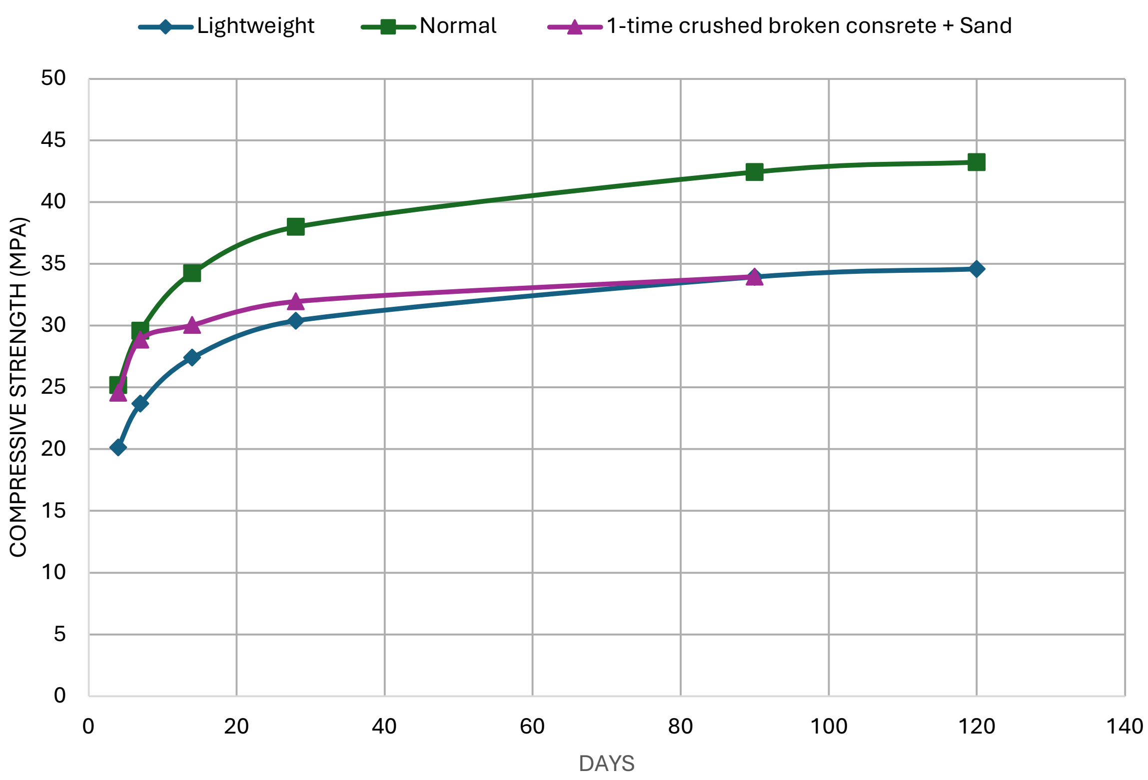


Figure 45. The results of compressive strength tests with respect to normal and lightweight concrete.

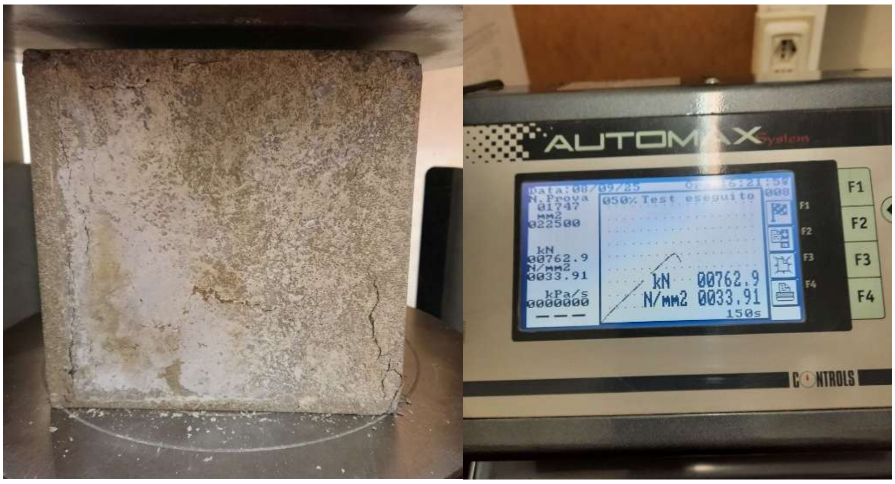


Figure 46. The failure crack pattern of the 90-day specimen.

5.8 *THREE-TIMES CRUSHED BROKEN CONCRETE + SAND*

The same procedure is carried out for the three times crushed broken concrete with additional sand to it. The granulometry test results are brought in the table below.

3 times crushed +Sand			
weight of sieves		Agg + sieve	Agg
25mm	1299	1299	0
19mm	1377	1377.5	0.5
12.5mm	1245	1375.5	130.5
9.5mm	1238	1776	538
6.3mm	1184	1869.5	685.5
4.75mm	1272	1676	404
2.36mm	1123	2131	1008
2mm	404.5	561.5	157
1.18mm	376	811	435
850μ	347.5	566	218.5
600μ	334	562.5	228.5
425μ	318	865.5	547.5
250μ	293	1010	717
150μ	280	579	299
75μ	266	369	103
Fondo	263	295.5	32.5
			5504.5
	Actual weight		5514
	Missing		9.5

Coarse aggregate	1758.5

Table 34. Three-times crushed Broken concrete + Sand table of granulometry data in the unitary of grams.

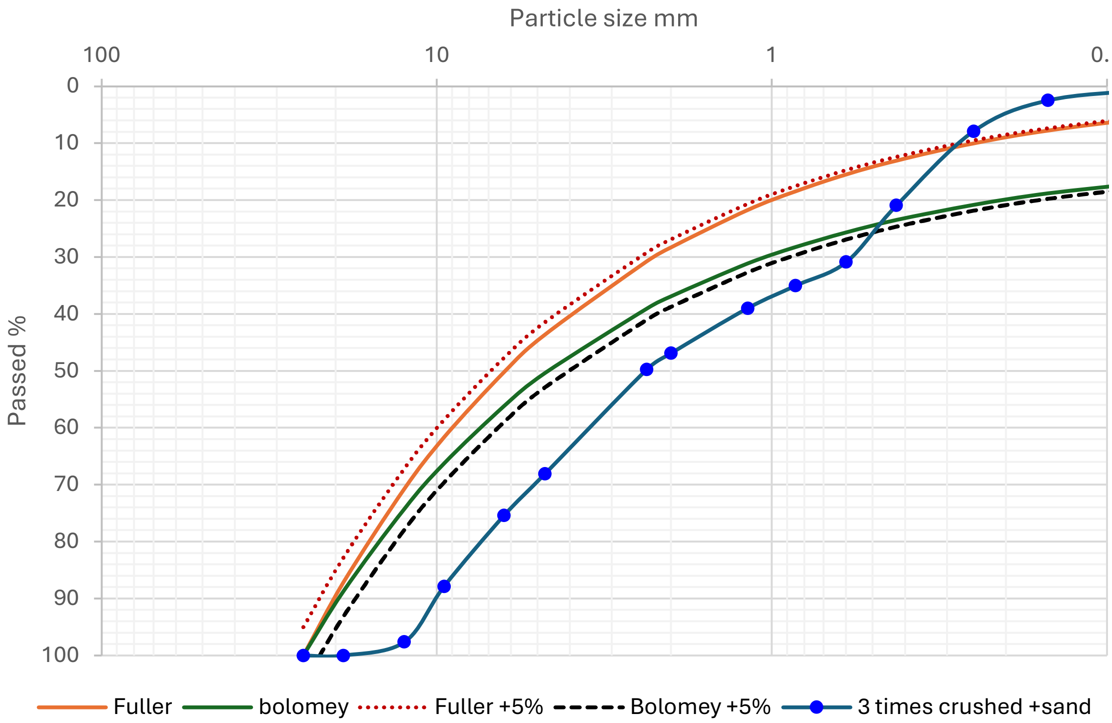


Figure 47. Three-times crushed Broken concrete + Sand graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The amount of sand was calculated in such way that each cube demanded 1 kilogram of sand. The water to cement ratio was considered 0.6. However, this proportion changed to 0.7 since additional water was added during the mix to reach the desired workability. Here are all the amounts of different materials used in the concrete, shown in the table below.

INPUT		
Title	**Value**	**Unit**
Water	**280**	*kg/m^3*
Cement	400	*kg/m^3*
Aggregate	1934	*kg/m^3*
Width of cube	0.15	*m*
Length of cube	0.15	*m*
Height of cube	0.15	*m*
Number of cubes	10	-
W/C	0.70	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2614**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**9.45**	*kg*
cement for all cubes	**13.5**	*kg*
Sand	**10**	*kg*
agg. For all cubes	**55.3**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**88.3**	*kg*

Table 35. Three-times crushed Broken concrete + Sand table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 5 ,7 ,14, 28 and 90 days there are two cubes to be broken. Instead of age 4, two cubes were broken in the fifth day since the fourth day after extraction was a holiday. Here is the table that shows the compressive strength of each cube in MPa.

	3 times crushed broken concrete +Sand					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	03-Jun-25					
Date of extraction	05-Jun-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 5	1	7.368	1	423.4	1	18.81
Day 5	2	7.384	2	406.2	2	18.05
Day 7	1	7.305	1	431.2	1	19.16
Day 7	2	7.2985	2	440.7	2	19.58
Day 14	1	7.153	1	444.7	1	19.76
Day 14	2	7.385	2	483.3	2	21.48
Day 28	1	7.3135	1	521.1	1	23.16
Day 28	2	7.115	2	446.8	2	19.86
Day 90	1	7.1975	1	514.9	1	22.88
Day 90	2	7.12	2	476.3	2	21.16

Table 36. The results of three-time crushed Broken concrete + Sand specimens after tests.

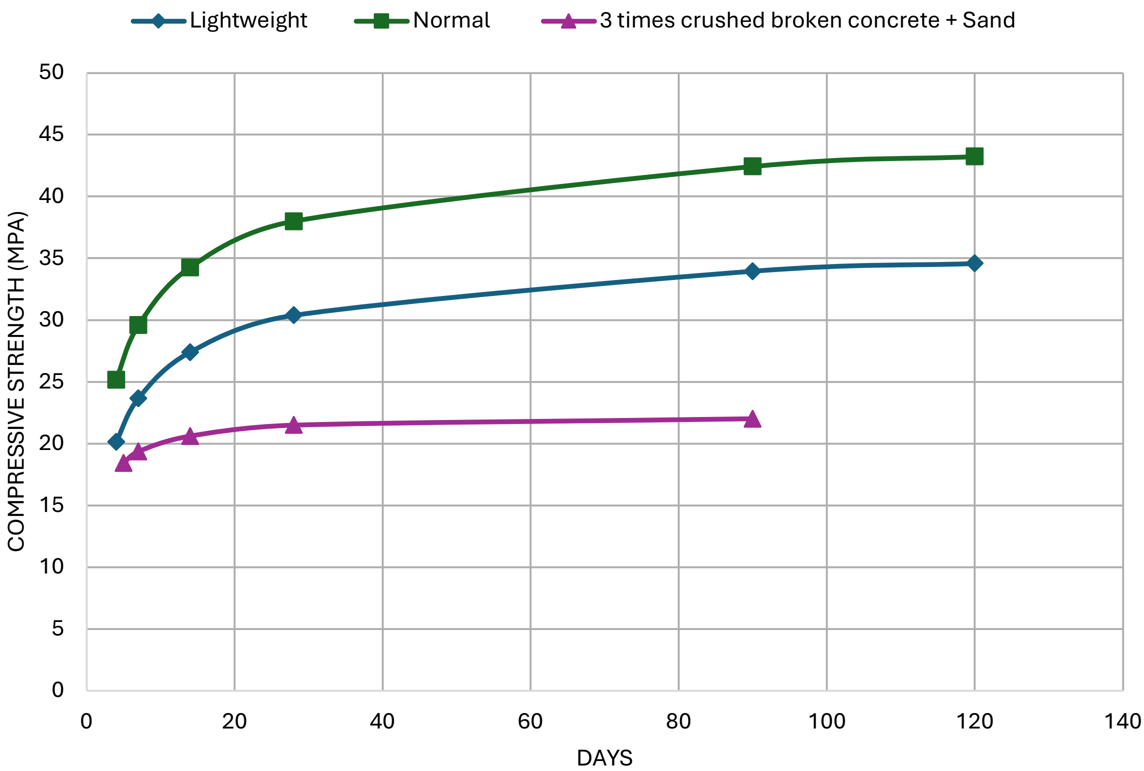


Figure 48. The results of compressive strength tests with respect to normal and lightweight concrete.

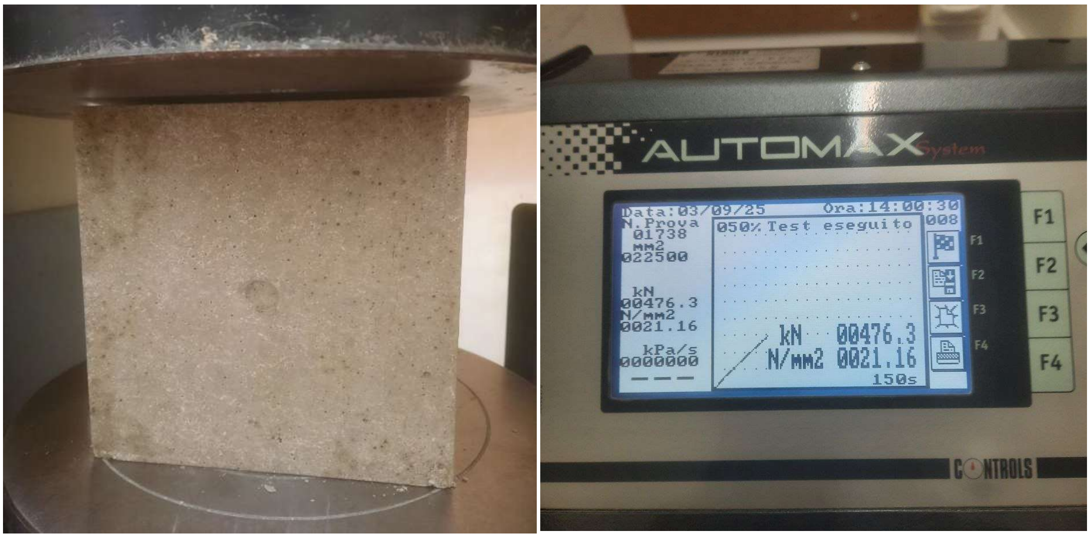


Figure 49. The failure crack pattern of the 90-day specimen.

5.9 ***ONE-TIME CRUSHED BROKEN CONCRETE + LIME***

The lime content was fixed at 5% by mass of cement to evaluate its influence on the properties of recycled aggregate concrete exclusively broken concrete aggregates. The table below shows the materials used in the concrete mix.

INPUT		
Title	**Value**	**Unit**
Water	**247.2**	*kg/m^3*
Cement	400	*kg/m^3*
Aggregate	1555	*kg/m^3*
Width of cube	0.15	*m*
Length of cube	0.15	*m*
Height of cube	0.15	*m*
Number of cubes	10	-
W/C	0.62	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2202.2**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**8.343**	*kg*
Lime	**0.675**	*kg*
cement for all cubes	**13.5**	*kg*
agg. For all cubes	**52.5**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**75.1**	*kg*

Table 37. One-time crushed Broken concrete + Lime table of materials.

Notably, the inclusion of lime resulted in a significant reduction in the effective water-to-cement ratio, decreasing from 0.73 in the reference mixture to 0.62 in the lime-modified system. This reduction suggests an improvement in particle packing and water demand, likely due to the filler effect and enhanced fines content introduced by lime.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 7 ,14, 28 and 90 days there are two cubes to be broken. Only age of 4 days yielded 1 cube since the couple was not extracted properly. Here is the table that shows the compressive strength of each cube in MPa.

	1-time crushed broken concrete +Lime					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	12-Jun-25					
Date of extraction	13-Jun-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.778	1	444.5	1	19.76
Day 4	2	-	2	-	2	-
Day 7	1	7.5465	1	463.2	1	20.59
Day 7	2	7.6885	2	459.5	2	20.42
Day 14	1	7.696	1	489.8	1	21.77
Day 14	2	7.641	2	509	2	22.62
Day 28	1	7.7115	1	536.4	1	23.83
Day 28	2	7.701	2	526.6	2	23.4
Day 90	1	7.7655	1	602.1	1	26.76
Day 90	2	7.779	2	564.9	2	25.1

Table 38. The results of one-time crushed Broken concrete + Lime specimens after tests.

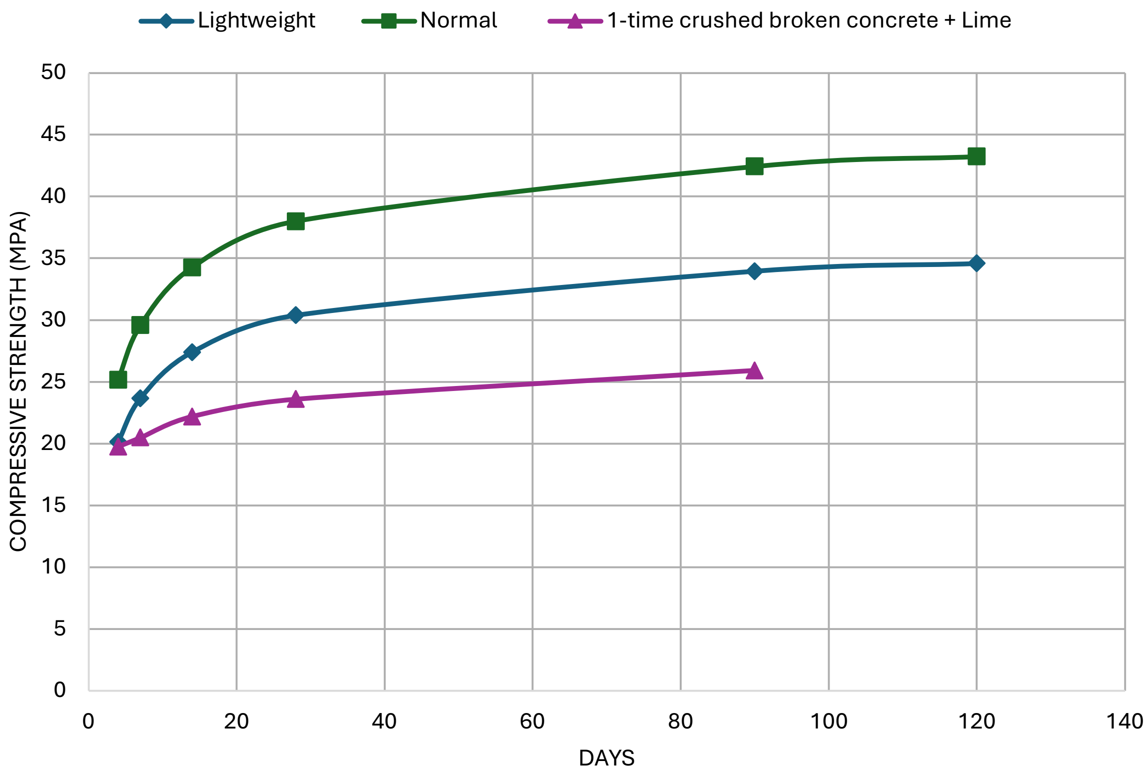


Figure 50. The results of compressive strength tests with respect to normal and lightweight concrete.

5.10 <u>*ONE-TIME CRUSHED BROKEN CONCRETE + SAND + LIME*</u>

In order to further investigate the combined influence of fines and chemical modification on recycled aggregate concrete, an additional series of mixtures was prepared incorporating both sand and lime alongside crushed concrete aggregates. This approach aimed to simultaneously address the granulometric deficiencies of recycled aggregates through sand addition, while introducing lime as a modifier of the cementitious environment. The inclusion of sand contributed to an improved particle size distribution and enhanced packing density, whereas lime increased the fines content and potentially influenced the interfacial transition zone (ITZ) and hydration processes. The combined use of these two components was expected to produce a synergistic effect, improving the overall compactness of the matrix and the quality of the bond between aggregates and paste.

However, it was expected that presence of lime might affect the overall compressive strength of concrete. Thus, for a comparative observation the same amounts, as the series of one-time crushed broken concrete with additional sand, and lime as 5% of the cement volume is added to the mixture. These mixtures were analysed in comparison with other configurations to isolate and better understand the individual and combined effects of sand and lime on the compressive strength and performance of the concrete.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The table below shows the amounts of materials used to make the concrete.

INPUT		
Title	**Value**	**Unit**
Water	**240**	*kg/m^3*
Cement	400	*kg/m^3*
Aggregate	1555	*kg/m^3*
Width of cube	0.15	*m*
Length of cube	0.15	*m*
Height of cube	0.15	*m*
Number of cubes	10	-
W/C	0.60	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2195**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**8.1**	*kg*
cement for all cubes	**13.5**	*kg*
Lime	**0.675**	*kg*
Sand	**10**	*kg*
agg. For all cubes	**52.5**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**84.8**	*kg*

Table 39. One-time crushed Broken concrete + Sand + Lime table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14, 28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	1-time crushed broken concrete +Lime + Sand					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	16-Jun-25					
Date of extraction	17-Jun-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.72	1	339.6	1	15.09
Day 4	2	7.653	2	363.7	2	16.16
Day 7	1	7.6135	1	391.6	1	17.41
Day 7	2	7.6935	2	395.1	2	17.56
Day 14	1	7.6415	1	424.7	1	18.88
Day 14	2	7.5665	2	423.2	2	18.8
Day 28	1	7.7025	1	460	1	20.44
Day 28	2	7.6525	2	496.7	2	22.07
Day 90	1	7.7325	1	531.2	1	23.6
Day 90	2	7.7895	2	508.2	2	22.59

Table 40. The results of one-time crushed Broken concrete + Sand + Lime specimens after tests.

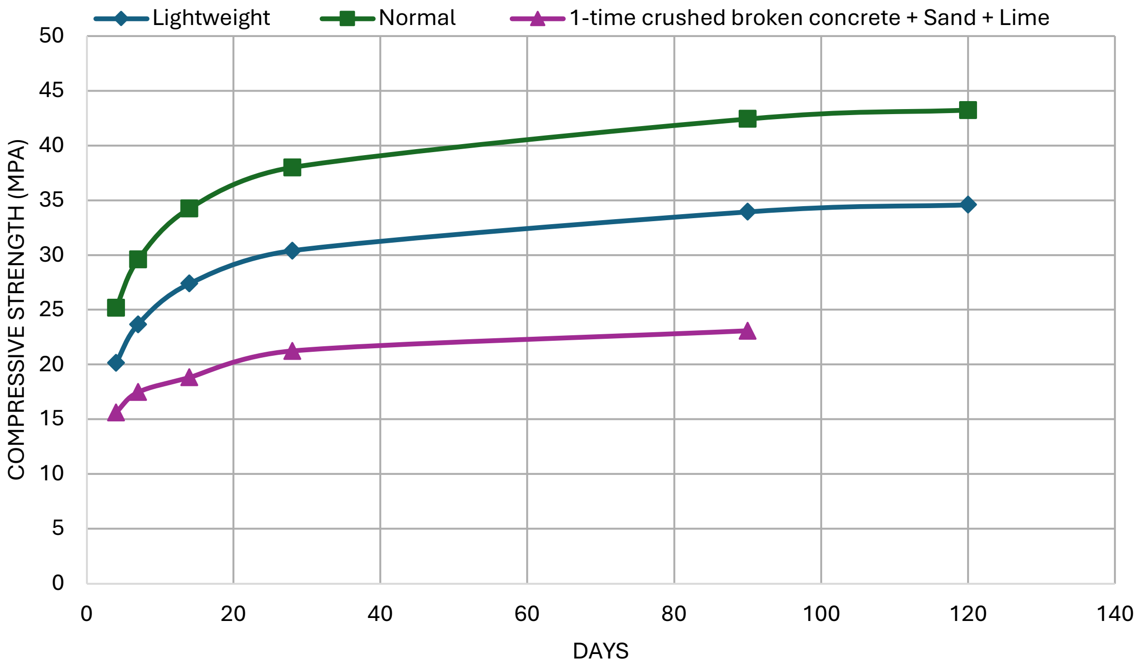


Figure 51. The results of compressive strength tests with respect to normal and lightweight concrete.

Figure 52.The failure crack pattern of the 90-day specimens.

5.11 <u>*ONE-TIME CRUSHED BROKEN CONCRETE + COARSE AGGREGATE + SAND*</u>

In addition to the previously described mixtures, a series of concrete samples was produced using recycled aggregates obtained from single-stage crushed concrete, combined with natural coarse aggregates and sand. The objective of this configuration was to improve the overall granulometric composition of the aggregate system while maintaining a predominantly recycled material base. The inclusion of natural coarse aggregates might lead to enhanced structural stability and mechanical interlocking, while the addition of sand served to correct the particle size distribution and reduce void content within the mix.

This combined approach was intended to achieve a more continuous grading curve, thereby improving packing density and promoting the formation of a denser and more homogeneous cementitious matrix.

Furthermore, the improved granulometry is expected to positively influence the quality of the interfacial transition zone (ITZ) between aggregates and paste, which plays a critical role in determining compressive strength. These mixtures were used as a reference framework to evaluate the effectiveness of granulometric optimization in recycled aggregate concrete systems. The granulometry test is executed and brought to the table below.

1-time crushed concrete + coarse agg + sand			
weight of sieves		Agg + sieve	Agg
25mm	1299	1299	0
19mm	1379	1470	91
12.5mm	1245	1777	532
9.5mm	1239	1948.5	709.5
6.3mm	1184	2045.5	861.5
4.75mm	1272.5	1673.5	401
2.36mm	1123	1904	781
2mm	405	480	75
1.18mm	376	623.5	247.5
850µ	347.5	470.5	123
600µ	334.5	485	150.5
425µ	319	782.5	463.5
250µ	294	945.5	651.5
150µ	280	530.5	250.5
75µ	266.5	354.5	88
Fondo	263	315	52
			5477.5
	Actual weight		5492.5
	Missing		15

Coarse aggregate	2595

Table 41. 1-time crushed Broken concrete + Coarse agg + Sand table of granulometry in unitary of grams.

Figure 53.The small coarse aggregates added in the mix. The picture is taken in the laboratory of university

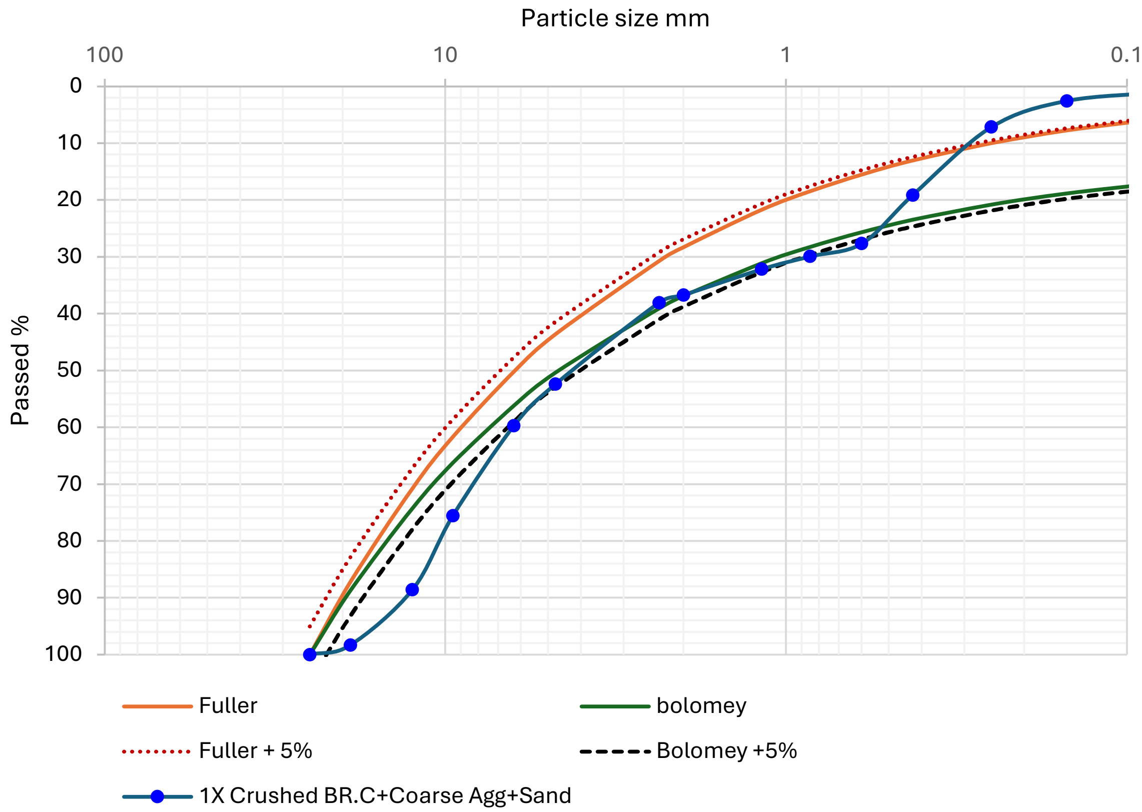


Figure 54. One-time crushed Broken concrete + Coarse aggregate+ Sand graph of granulometry and the fuller and bolomey criterions.

A total of ten concrete cubes were expected, and this requirement was satisfactorily met. The amount of sand was calculated in such way that each cube demanded 1 kilogram of coarse aggregate and the whole amount of added sand was 13.3 kilogram. The water to cement ratio was considered 0.6. However, this proportion changed to 0.76 since additional water was added during the mix to reach the desired workability. Here are all the amounts of different materials used in the concrete, shown in the table below.

INPUT		
Title	**Value**	**Unit**
Water	**313.6**	*kg/m^3*
Cement	400	*kg/m^3*
Aggregate	1555	*kg/m^3*
Width of cube	0.15	*m*
Length of cube	0.15	*m*
Height of cube	0.15	*m*
Number of cubes	10	-
W/C	0.78	-

OUTPUT		
title	**value**	**unit**
volume of 1 cube	**0.003375**	*m^3*
total volume	**2268.6**	*kg/m3*
Total cube volume	**0.03375**	*kg/m3*
Water for all cubes	**10.58**	*kg*
cement for all cubes	**13.5**	*kg*
Coarse aggregates	**10**	*kg*
Sand	**13.3**	*kg*
agg. For all cubes	**52.5**	*kg*
Additive	**0.0675**	*kg*
total cube weight	**99.9**	*kg*

Table 42. One-time crushed Broken concrete + Coarse aggregate + Sand table of materials.

After casting the concrete and extracting the cubes, they are soaked in the water with fixed temperature, and the compressive strength test is executed. For each age of 4 ,7 ,14, 28 and 90 days there are two cubes to be broken. Here is the table that shows the compressive strength of each cube in MPa.

	1-time crushed broken concrete +coarse aggregate+sand					
Number of specimens	10					
Dimension of cubes	0.15*0.15*0.15					
Date of setting	17-Jun-25					
Date of extraction	19-Jun-25					
	Weight of the aged specimen (kg)		Total resistance (kN)		Unitary resistance (mpa)	
Day 4	1	7.642	1	209.8	1	9.32
Day 4	2	7.64	2	212.8	2	9.46
Day 7	1	7.573	1	225	1	10
Day 7	2	7.502	2	236.8	2	10.52
Day 14	1	7.5805	1	271.8	1	12.08
Day 14	2	7.633	2	256.2	2	11.39
Day 28	1	7.5795	1	288.6	1	12.83
Day 28	2	7.7615	2	283.5	2	12.6
Day 90	1	7.513	1	316.4	1	14.06
Day 90	2	7.628	2	292.3	2	12.99

Table 43. The results of one-time crushed Broken concrete + Coarse aggregate +Sand specimens after tests.

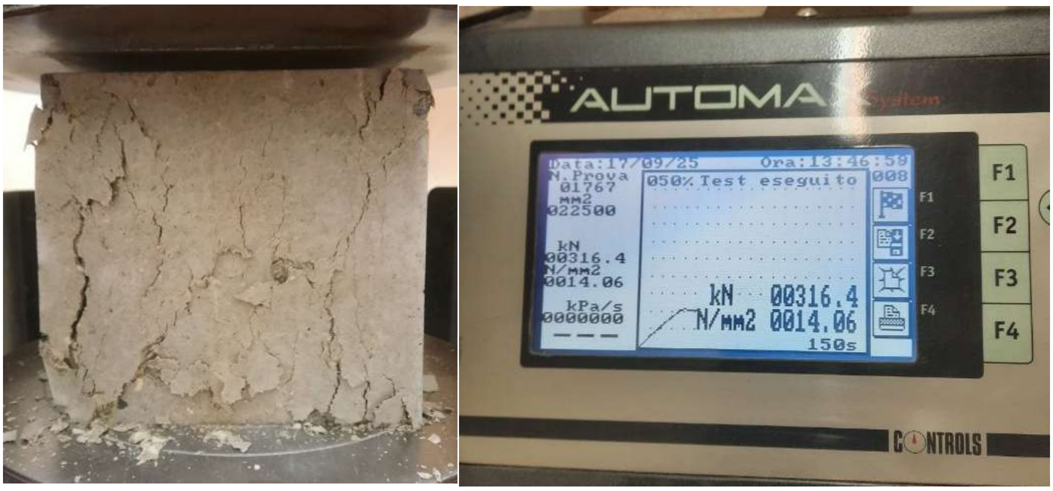


Figure 55.The failure crack pattern of the 90-day specimen

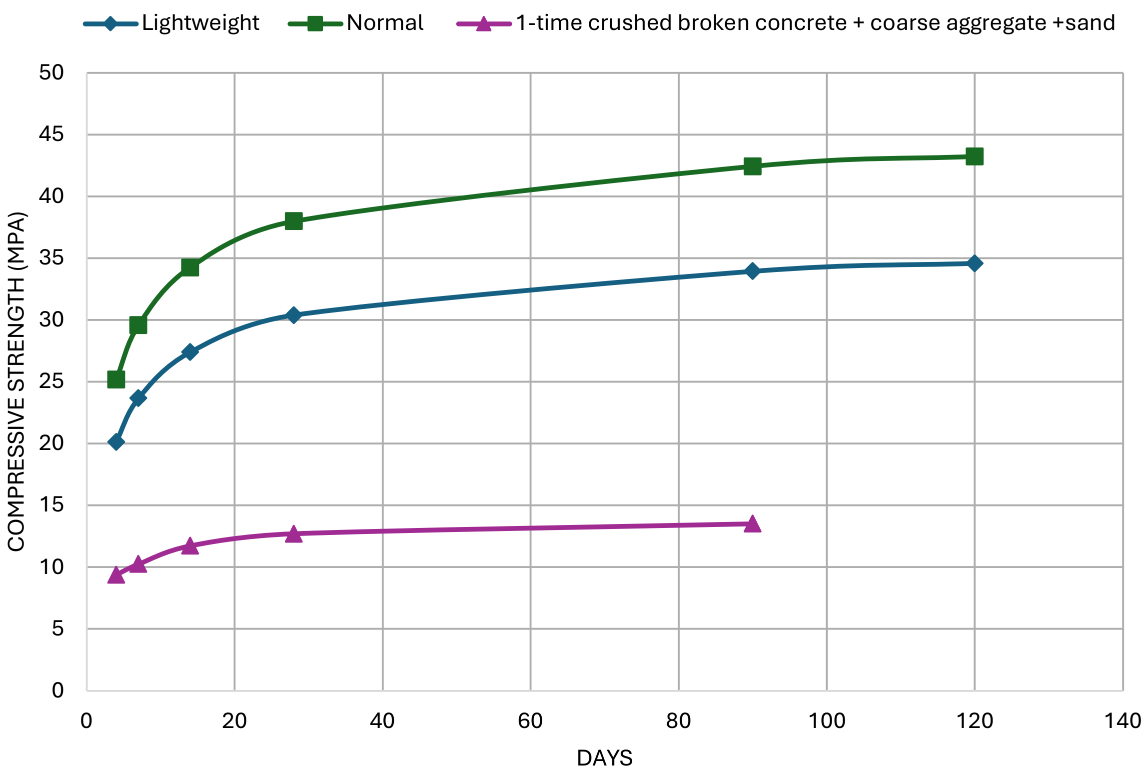


Figure 56. The results of compressive strength tests with respect to normal and lightweight concrete.

In contrast to expectations, the concrete mixtures incorporating recycled aggregates from crushed concrete in combination with natural coarse aggregates and sand did not exhibit an improvement in mechanical performance. Despite the intended enhancement of granulometric distribution through the addition of sand and the inclusion of coarse aggregates to improve structural stability, the results suggest that these modifications alone were insufficient to produce a denser and more effective matrix. What was observed was that aggregates of broken concrete with adhered cement and coarse aggregates needed more Cementous paste to fill in the voids.

This behaviour may be attributed to the inherent properties of recycled aggregates, such as higher porosity, increased water absorption, and the presence of adhered mortar, which can negatively affect the quality of the interfacial transition zone (ITZ). Furthermore, the mismatch between the physical properties of natural and recycled aggregates may have led to suboptimal bonding and stress distribution within the concrete. Meanwhile, the additional water may lead to have a less compressive strength.

These findings indicate that granulometric optimization, while important, is not solely sufficient to guarantee improved compressive strength, highlighting the need for additional modifications, such as chemical treatment or further refinement of the mix design.

Chapter 6: Conclusion

6.1 ***Discussion of results***

The results confirm that such materials can be used in concrete production; however, the mechanical performance is strongly influenced by the nature of the aggregates, grading, their processing, and the overall mix design.

The compressive strength results highlight a significant variability, particularly in mixes containing mixed debris aggregates. Specimens prepared under controlled mixing conditions achieved notably higher strength than those produced with less consistent procedures, emphasizing the importance of proper mixing and quality control. Moreover, increasing the number of crushing cycles did not result in systematic improvements; in some cases, excessive crushing led to reduced strength, likely due to the generation of weaker particles and a higher fines content, which adversely affect the interfacial transition zone.

Concrete produced with recycled concrete aggregates showed more consistent but moderate strength values. However, the addition of sand and lime contributed to a clear improvement in performance, indicating that appropriate particle grading and matrix densification play a key role in enhancing the properties of recycled aggregate concrete.

From a practical perspective, direct observation during the mixing process provided further insight into these results. The addition of water required careful control, as the recycled aggregates exhibited variable absorption behaviour. Furthermore, the incorporation of sand improved the workability and cohesion of the mix, while lime appeared to enhance the binding effect, resulting in a more homogeneous and stable material. These observations support the experimental findings and highlight the importance of mix adjustments when working with recycled materials.

Substantially, the specimens of one-time crushed broken concrete and sand resulted better than the others. To reason that, it is related to the replacement ratio (RR) of aggregates which was questioned before in this thesis. Meaning that, sand in the mix acted as natural aggregates which was combined with aggregates from crushed broken concrete with adhered cement.It also filled most of the voids and increased density.

In conclusion, recycled aggregate concrete represents a viable and more sustainable alternative to conventional concrete; however, its performance remains sensitive to material variability and processing conditions. Its use should therefore be accompanied by careful mix design and quality control, particularly when aiming for structural applications.

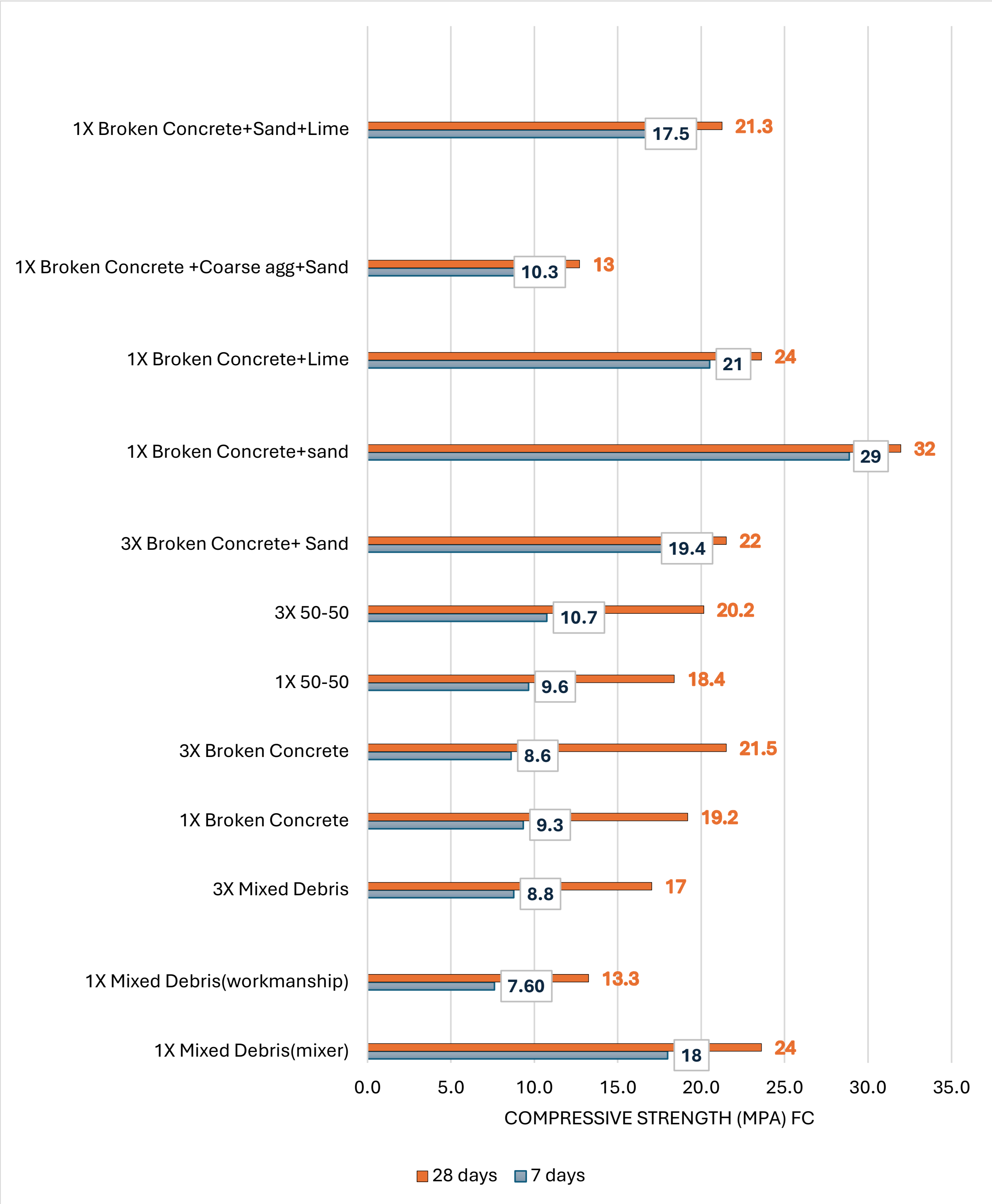


Figure 57. The comparative chart of the series of concrete with respect to their compressive strength in 7 and 28 days.

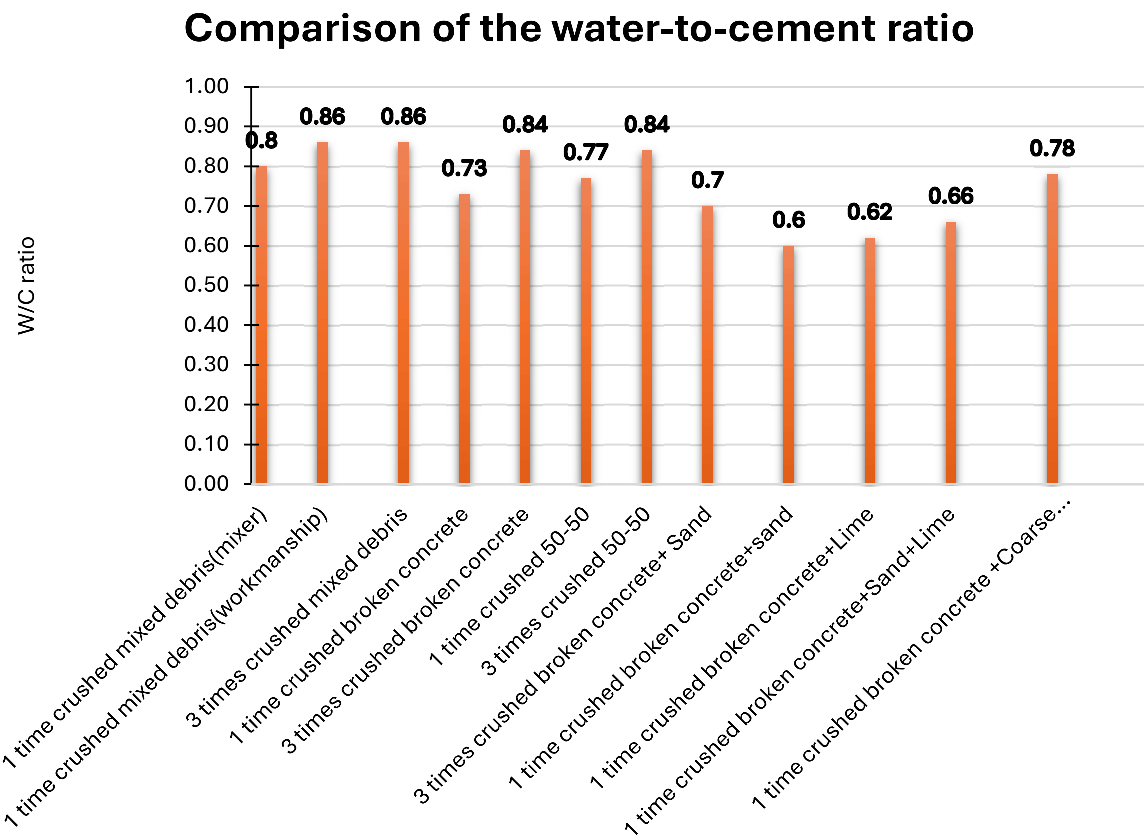


Figure 58. The comparison of the water to cement ratio of the series used to achieve the desired workability.

6.2 *Future studies*

Although numerous studies have focused on chemical and mineral enhancement techniques for recycled aggregate concrete (RAC), the present research suggests that significant improvements may also be achieved through optimized aggregate processing and granulometric control. Therefore, future investigations should further explore low-intervention and practical approaches capable of improving RAC performance without excessive dependence on supplementary chemical treatments.

One important direction for future research is the optimization of crushing methodologies. The results of this study indicate that repeated crushing cycles substantially influence particle shape, density, adhered mortar removal, and overall grading quality. Further studies should investigate the relationship between crushing energy, number of crushing stages, and resulting mechanical performance to determine the optimal balance between aggregate quality and energy consumption.

Additionally, future experimental campaigns should focus on advanced granulometric optimization using packing density models. While Fuller and Bolomey criterions provide useful theoretical references, other particle packing models such as Andreasen and Funk–Dinger distributions could be evaluated for recycled aggregates with irregular particle morphology.

Another important topic is the selective separation of demolition waste prior to crushing. Since mixed debris introduces significant variability in water absorption and density, future studies should investigate how pre-sorting techniques may improve the homogeneity of recycled aggregates while maintaining practical feasibility for on-site recycling operations.

Further research is also recommended on the combined effect of granulometric optimization and minimal natural aggregate correction. The present study demonstrated that the addition of sand improved grading continuity and workability. Future work could identify the minimum quantity of natural aggregate required to achieve acceptable structural performance while maximizing recycled content.

From a practical perspective, future research should also assess the feasibility of decentralized urban recycling systems using portable crushing equipment, particularly in dense historical cities such as Genoa where transportation and large-scale processing are difficult. The integration of on-site crushing, sieve analysis, and optimized grading may represent an economically and environmentally sustainable alternative for circular construction practices.

Finally, future studies could investigate the application of artificial intelligence and image-analysis techniques for real-time granulometric monitoring of recycled aggregates. Such systems may enable automated quality control and continuous optimization of aggregate grading during the recycling process, improving consistency and reducing variability in RAC production.

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