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KEY INFLUENCING FACTORS IN CONCRETE WORKABILITY AND DURABILITY WHEN USING PLASTIC AGGREGATES – TECHNOLOGICAL APPROACH

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Abstract: While several studies have explored the technical feasibility and mechanical attributes of concrete blends incorporating different proportions of plastic waste as aggregate substitutes, this research aims to further explore the broader implications of utilizing plastic waste in concrete. It will examine its effects on the overall workability and durability of concrete and the key factors which have various influences. The improvement in concrete workability when using plastic aggregates is driven by several key factors related to the physical and chemical properties of the plastics and their interaction with the concrete matrix. In fact, the concrete's workability improvements with plastic aggregates are primarily due to their smooth surface, rounded shape, low water absorption, and the proportion and type of plastic used. These factors combine to reduce internal friction and retain more free water in the mix, making the concrete easier to mix, transport, and place. According to these key factors, the long–term durability effects of using different plastics in concrete are influenced by the type of plastic, its particle size and shape, surface properties, and interaction with the cement matrix. While plastic aggregates reduce density and improve workability, their typical hydrophobic and smooth surfaces weaken bonding with cement paste, leading to reduced strength and poorer freeze–thaw durability. However, with careful selection of plastic type, particle size, surface treatment, and conservative replacement levels (commonly below 10–15%), acceptable long–term durability can be achieved.
Keywords: concrete, workability, durability, key factors, various types of plastics

1. ABOUT THE SUSTAINABLE CONCRETE

Sustainable concrete offers a promising solution to the environmental and social challenges posed by conventional concrete production.[1] By addressing key issues such as resource depletion and waste generation, it presents a multifaceted approach to sustainable construction. By integrating alternative binders and recycled materials, sustainable concrete significantly promotes resource conservation.[2] Moreover, its emphasis on energy efficiency and waste reduction aligns with the principles of a circular economy, fostering environmental stewardship. The durability and longevity of sustainable concrete structures not only minimize environmental impact but also reduce the need for costly repairs and replacements, ensuring economic efficiency over the long term. Furthermore, innovations in sustainable concrete formulations continually enhance performance characteristics, contributing to the overall resilience and sustainability of built environments.[1,2]

The sustainable construction materials can reduce the amount constitutive elements of concrete required for civil constructions. Therefore, different recycled materials, organic aggregates and synthetic fibers used in sustainable concrete. The recycled materials include rubber, plastic, glass and industrial waste.[3–7] The organic aggregates consider the bamboo, coconut fiber and nanocellulose. On the other hand, the synthetic and mineral fibers use steel, glass, carbon and textile fiber and epoxy resins.

The use of concrete in civil infrastructure is highly demanded in structural and non–structural elements. However, the high production of concrete could lead to severe pollution in the world. This pollution can be decreased using sustainable materials mixed with cement to obtain sustainable concrete.[3–7] Recycling plastic waste to create sustainable construction materials, such as concrete, has emerged as a promising approach. By recycling plastic waste into concrete, the construction industry can reduce dependence on natural aggregates and minimize environmental pollution.[7]

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The solution to the plastic–related problem lies in utilizing plastics in construction.[7] Concrete, being one of the most used construction materials globally, requires a substantial number of natural aggregates annually. This expanding request for development materials produces a shortage of normal assets.[8,9] In any case, to manage this request, specialists are reacting emphatically by proposing unused details of utilizing elective materials. Incorporating plastic waste into concrete can reduce dependency on natural aggregates, thereby reducing associated manufacturing and transportation expenses. Hence, it facilitates the disposal of waste materials without environmental impact. Efficient valorization of plastic waste is widely investigated by numerous researchers. The need for an alternate to conventional aggregate in concrete production has led to the evolution of numerous artificial aggregates.[6,9–11,15]

Various types of plastics, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), high–density polyethylene (HDPE), and low–density polyethylene (LDPE), can serve as additives in concrete, typically in the forms of fibers, particles, or aggregates.[6–13] Each plastic type possesses distinct properties that can enhance specific characteristics of concrete. For instance, the inclusion of plastic fibers can bolster concrete's toughness and longevity, while employing plastic aggregates can reduce its density. Also, plastics can contribute to improving concrete's ductility, impact resistance, and thermal properties. Integrating plastics into concrete mixtures can result in construction projects benefiting from heightened performance and sustainability.[1,2,14,19]

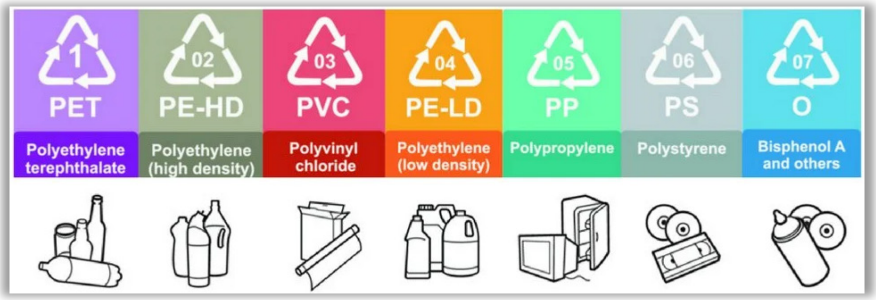

Figure 1. Types of plastics

Utilizing plastic waste in concrete poses a potential solution for waste management while offering intriguing possibilities for improving workability and creating lightweight concrete.[7] However, it is crucial to acknowledge that this approach is still evolving, and its long–term implications on economic viability and overall performance require further research and optimization. Carefully evaluating the potential benefits and considerations mentioned above, including workability, durability and weight impact, is essential before the widespread adoption of this approach in construction practices.[21–23] Additionally, ensuring the structural integrity, durability, and environmental sustainability of plastic–containing concrete over its life cycle remains paramount.

The use of plastic waste as the replacement for fine and coarse aggregate will increase the workability of the mix due to the smooth surface texture and lower water absorption of plastic particles.[12,14,18] However, it's important to note that while workability may improve, other mechanical properties like compressive and tensile strength often decrease, especially at higher replacement levels. Thus, the main motivation for using plastic waste in concrete remains environmental—reducing landfill and pollution—rather than enhancing concrete's technical performance.[16,17]

2. FACTORS INFLUENCING WORKABILITY IMPROVEMENTS WITH PLASTIC AGGREGATES

The incorporation of recycled plastic aggregates in concrete significantly impacts both workability and durability through several interconnected mechanisms.[13,23]

- FRESH CONCRETE BEHAVIOR: Plastic aggregates affect segregation and bleeding characteristics differently than natural aggregates. While the hydrophobic nature reduces bleeding by limiting water migration, the density difference between plastic and natural aggregates can promote segregation if not properly managed.

The reduced water absorption of plastic particles maintains higher free water content, which can improve consolidation but may increase bleeding risk in poorly designed mixtures. [13,23]

- FREEZE–THAW DURABILITY: Concrete containing plastic aggregates exhibits poor freeze–thaw resistance due to several factors:
- — differential thermal expansion: Plastic aggregates have different thermal expansion coefficients compared to cement paste, creating internal stresses during temperature cycles
- — increased porosity: Weak bonding creates pathways for water ingress and expansion
- — reduced cohesion: The hydrophobic nature prevents proper water distribution, making the concrete more susceptible to freeze–thaw damage

The weak interfacial transition zone (ITZ) between plastic aggregates and cement paste represents the most critical durability concern. The smooth, hydrophobic surface of plastic particles creates poor mechanical bonding with the cementitious matrix.

- AIR CONTENT AND SEGREGATION: Smooth plastic surfaces tend to increase air entrainment due to their hydrophobic nature, modifying fresh concrete rheology. However, if not properly controlled, differences in density and surface characteristics may lead to segregation issues at higher replacement ratios.

The initial hydrophobic and smooth nature of plastic aggregates enhances fresh concrete workability but may weaken the bond at the interfacial transition zone (ITZ), affecting durability. Roughened surfaces enhance ITZ bonding and mechanical strength but reduce the ease of flow and workability.

3. INFLUENCES ON CONCRETE WORKABILITY WHEN USING PLASTIC AGGREGATES

The improvement in concrete workability when using plastic aggregates is driven by several key factors related to the physical and chemical properties of the plastics and their interaction with the concrete matrix. Understanding these key factors is crucial for optimizing the performance of plastic aggregate concrete.[18–25]

Plastic waste can improve the workability of concrete primarily due to its physical characteristics, despite its use being driven by waste management rather than performance enhancement. The key reasons are:

- SURFACE TEXTURE OF PLASTIC AGGREGATES

The surface texture of plastic aggregates represents one of the most critical factors affecting fresh concrete workability, fundamentally altering the mixing behaviour, flow characteristics, and overall handling properties of concrete mixtures:

- — SMOOTH SURFACE: Plastic particles tend to have a smoother surface compared to natural aggregates. This reduces internal friction within the mix, allowing concrete to flow more easily and increasing the slump value, a direct measure of workability. Smoother surfaces increase workability. The smooth surface texture of plastic aggregates acts as a lubricant, reducing internal friction between particles and enhancing flowability.
- — BONDING WITH CEMENT PASTE: Smoother surfaces can also result in weaker bonds with the cement paste, which further reduces friction and enhances workability.

The surface texture of plastic aggregates significantly influences the workability of concrete by affecting the lubrication and inter–particle friction; smooth surfaces enhance flow and reduce internal resistance, thereby improving workability, while rough or flaky textures increase interlocking and friction, leading to reduced flowability and potential challenges in mixing and placement. In summary, the smooth surface texture of plastic aggregates improves the workability of fresh concrete by reducing friction and increasing slump, while increased surface roughness

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improves mechanical bonding but lowers workability. Practical use requires balancing these effects based on application requirements and mixing designs.

Figure 2. Plastic flakes

The design of plastic aggregate shapes can significantly optimize concrete's durability by improving the mechanical interlocking and bonding at the interfacial transition zone (ITZ) between the plastic aggregates and the cement paste, which is typically a weak point affecting durability.

SHAPE AND SIZE OF PLASTIC PARTICLES

The particle shape and size distribution critically influence workability. Angular and flaky plastic particles increase the specific surface area requiring more cement paste for coating, while spherical particles improve flow characteristics. Research shows that flaky PET particles reduce workability more significantly than spherical pellets.

Figure 3. Plastic particle shape and size

Particle geometry critically influences workability characteristics:

- PARTICLE SHAPE: Rounded or semi–spherical plastic aggregates increase workability by acting like tiny ball bearings, reducing resistance to movement. In contrast, angular plastic particles can decrease workability due to increased inter–particle friction:
  - Rounded shapes improve workability. Spherical and cylindrical particles enhance workability by minimizing particle interlocking and reducing mixing resistance
  - Flaky and angular particles decrease workability due to increased specific surface area requiring more paste for coating and higher inter–particle friction
- PARTICLE SIZE: Smaller and more uniform plastic particles can help maintain a consistent mix, while larger or irregularly shaped particles may disrupt flow and reduce workability. Particle size affects workability with smaller particles generally providing better flow characteristics, though larger particles (up to optimal limits) can improve lubricating effects

Plastic waste, especially in the form of flakes or rounded particles, can act as "ball bearings" within the mix, reducing resistance to movement and making the fresh concrete easier to handle and place. Studies show that semi–spherical plastic particles with smooth surfaces significantly enhance workability and reduce water–cement ratios, while angular and non–uniform shapes diminish workability and require additional water.

Larger and irregular shapes often cause more voids and defects in the matrix, reducing strength faster than smaller or more uniformly shaped particles. Studies report that mixes with larger plastic

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particles suffer more from strength loss than those with smaller, well–graded particles. Optimizing shape is therefore key to balancing workability and strength in recycled plastic aggregate concrete.

WATER ABSORPTION CHARACTERISTICS

The hydrophobic nature of plastic particles is a fundamental factor affecting workability and alters concrete workability by eliminating water absorption during mixing. This characteristic results in an increased free water content in the mixture, improving flowability and consistency.

The water absorption characteristics of plastic aggregates significantly influence the workability of concrete, primarily due to their near–zero or very low water absorption capacity compared to natural aggregates:

- LOW WATER ABSORPTION: Unlike natural aggregates, plastic particles do not absorb water during mixing, which increases the available free water in the mixture and generally improves workability. Plastics generally absorb less water than natural aggregates. This leaves more free water in the concrete mix, making it easier to handle and place. Lower absorption increases free water. Plastic aggregate concretes generally show water absorption around 1.3%, which is comparable or slightly lower than conventional concrete, indicating minimal absorption by plastic particles, preserving free water in the mix. As a result, more free water remains in the mixture, further enhancing workability.
- EFFECT ON WATER–CEMENT RATIO: Because less water is absorbed by the aggregates, the effective water–cement ratio is higher, which typically improves workability. Since plastic aggregates do not absorb water, the water demand of the concrete mix decreases relative to using natural aggregates. This helps maintain better consistency and easier placing without increasing water–cement ratio
- EFFECT ON BLEEDING AND SEGREGATION: While increased free water improves workability, it can also increase the risk of bleeding and segregation, especially at higher replacement levels if not properly managed during mix design and compaction

In summary, the low or negligible water absorption of plastic aggregates increases the free water in the mix, enhancing fresh concrete workability by improving flowability and slump. However, the mix design must carefully control water content and use admixtures as necessary to prevent excess bleeding and segregation risks. The higher free water content can also increase the risk of segregation and bleeding if not controlled through proper mix design and the use of admixtures. Studies show pre–saturation of plastic aggregates does not improve bonding or strength and may worsen mechanical performance, so dry plastic aggregates are generally preferable to maintain workability benefits. Overall, the water absorption characteristics of plastic aggregates increase mix flowability and workability by preserving more free water in the mix, but require careful balance to avoid negative effects on mixture stability.

PLASTIC CONTENT (DOSAGE)

The dosage or content of plastic aggregates in concrete has a clear and significant influence on its workability, generally leading to improved workability as plastic aggregate content increases, up to certain limits:

- PROPORTION OF PLASTIC AGGREGATE: Higher content generally increases workability. Increasing the percentage of plastic aggregate generally leads to higher workability, up to a certain threshold. Beyond this, excessive plastic content can introduce too much porosity or disrupt the matrix, potentially reducing workability or compromising other properties.

Workability improvement typically increases with plastic aggregate content up to an optimal replacement level. Studies demonstrate that slump values can increase with plastic aggregate replacement ranging from 5–30%. However, excessive replacement (>15–20%) can lead to harsh mixtures with segregation and bleeding issues

- OPTIMAL REPLACEMENT LEVELS FOR BALANCED PERFORMANCE: While workability improves with increasing plastic content, there is an optimal range beyond which problems arise. Replacement levels around 5–15% often provide the best balance of improved workability without excessive segregation or bleeding risks. Very high plastic contents (>20–30%) can cause segregation due to the density difference between plastic and natural aggregates, possibly destabilizing the fresh mix

Increasing the plastic aggregate dosage in concrete generally enhances workability by increasing free water and reducing friction, but it must be controlled to avoid mix instability. Typical recommended replacement ranges for optimizing workability are around 5–15%, varying by plastic type and particle characteristics.

TYPE OF PLASTIC USED

The type of plastic used as aggregate in concrete significantly influences its workability due to differences in surface texture, shape, density, and hydrophobicity among plastic types:

- DIFFERENT PLASTICS HAVE DIFFERENT EFFECTS: The type of plastic (e.g., PET, HDPE, PVC) influences workability due to variations in surface texture, density, and compatibility with cement paste. For example, PET tends to provide better workability improvements than HDPE or PP, which may have smoother surfaces and weaker bonds. PET often more beneficial than HDPE or PP.
- PLASTIC AGGREGATES SIGNIFICANTLY INFLUENCE SHRINKAGE BEHAVIOR:
  - PVC aggregates: Reduce drying shrinkage due to low thermal conductivity and reduced evaporation rates
  - HDPE aggregates: Increase shrinkage due to higher porosity and weak bonding
  - PET aggregates: Generally increase shrinkage proportional to replacement percentage
- THE SPECIFIC PLASTIC TYPE AND PARTICLE SHAPE INTERACT WITH DOSAGE EFFECTS: PVC aggregates can often be used up to about 30% with good workability, whereas PET and HDPE typically have lower optimal replacement percentages (5–10% for PET, 2–5% for HDPE). Smooth, rounded particles improve workability more than angular or flaky shapes due to lower friction.

In summary, smooth and hydrophobic plastics like PP and HDPE improve concrete workability by increasing slump through enhanced lubrication and water retention, but may reduce cement bonding and strength if used in high proportions. Flaky and irregular shaped plastics like PET tend to reduce workability but with appropriate surface treatments can improve bonding and strength. PVC generally allows a wider range of replacement with moderate effects on workability.

Thus, the type of plastic aggregate profoundly affects concrete workability by influencing water retention, particle friction, and paste demand, and must be selected and dosed according to desired fresh concrete behavior and strength requirements. The key factors affecting the workability of fresh concrete with recycled plastic aggregates include the particle shape and size distribution, the hydrophobic and smooth surface characteristics of the plastic, the percentage of plastic aggregate replacement, and the resulting influence on segregation, bleeding, and water content management within the mixture. In summary, workability improvements with plastic aggregates are primarily due to their smooth surface, rounded shape, low water absorption, and the proportion and type of plastic used. These factors combine to reduce internal friction and retain more free water in the mix, making the concrete easier to mix, transport, and place.

4. INCORPORATING PLASTIC WASTE AND INFLUENCE ON WORKABILITY AND DURABILITY

INFLUENCE ON WORKABILITY

The incorporation of recycled plastic aggregates in concrete affects workability and durability in distinct ways. Workability pertains to the ease of mixing, placing, compacting, and finishing fresh concrete. Incorporating plastic waste can potentially influence this property in several ways:

- IMPROVED WORKABILITY: Replacing natural sand with recycled plastic aggregates generally increases the slump and flowability of fresh concrete. This improvement is mainly due to the hydrophobic nature of plastic particles, which reduces water absorption and acts somewhat like a lubricant in the mix, leading to higher slump values and easier placement. Certain types of plastic, particularly fibers, act as lubricants, reducing friction between the concrete particles. This can lead to smoother flow, improved pumpability, and easier finishing, potentially translating to reduced labor costs and increased construction efficiency.
- REDUCED WATER DEMAND: few researchers indicate that integrating particular types of plastic waste, such as PET flakes, may enable a modest decrease in the water–to–cement ratio while preserving workability. This could result in more compact concrete with potentially enhanced strength and durability.
- POTENTIAL DRAWBACKS: Utilizing large quantities of plastic aggregates, particularly irregular shapes, can hinder workability. Additionally, some plastics may require surface treatment to ensure proper compatibility with the cement, impacting the mixing process.
- Studies have shown that even at low replacement levels (e.g., 5–10%), workability is enhanced without compromising mix consistency. For example, slump values increased from 80 mm in control mixes to as high as 190 mm with plastic replacement, indicating better flowability.
- The shape and size of plastic particles also influence workability; smaller, rounded particles similar in size to sand improve uniformity and flow better than irregular shapes.

INFLUENCE ON DURABILITY

The long–term performance and durability of concrete containing plastic remain uncertain and require further investigation. The type of plastic influences concrete durability through its surface roughness, chemical stability, density, and elastic properties, impacting mechanical strength, porosity, permeability, environmental resistance, and bond strength. Polyethylene–based plastics (PE, PP) and PET are most studied, with moderate replacement levels recommended to mitigate durability loss. More research is ongoing to optimize treatments and understand long–term chemical and physical interactions. Several factors contribute to this uncertainty:

- WEATHERING AND DEGRADATION: Plastic materials can be susceptible to degradation from various environmental factors like sunlight, heat, and freeze–thaw cycles. This degradation can weaken the plastic over time, potentially impacting the overall durability of the concrete and leading to long–term performance issues.
- REDUCED DURABILITY UNDER FREEZE–THAW CYCLES: Concrete with recycled plastic aggregates tends to show poor resistance to freezing and thawing, with significant compressive strength losses (up to 80%) and increased brittleness after multiple cycles. This is attributed to differential thermal expansion between plastic and cement matrix and weaker bonding at the plastic–concrete interface.
- LOWER DENSITY AND WEAKER BONDING: The lower density and incompatibility of plastic particles reduce the overall density and cohesion of hardened concrete, leading to decreased compressive and tensile strength as plastic content increases.
- CHEMICAL REACTIONS: Interactions between certain plastics and the cement matrix over extended periods are not fully understood. Potential chemical reactions could affect the properties of the concrete and lead to unforeseen consequences for its performance and durability.
- LIMITED DATA: Long–term data on the performance of plastic–containing concrete in real–world applications is currently limited. This makes it challenging to definitively assess its suitability for various construction projects and predict its long–term behaviour.

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- TENSILE STRENGTH IMPACT: Tensile strength shows a relatively minor decrease at low replacement levels but declines more noticeably at higher plastic contents due to voids and weak bonding.
- POTENTIAL FOR IMPROVEMENT: Chemical treatment of plastic particles or optimizing particle size and shape can mitigate some durability issues, but further research is needed.

Summary Table

Property	Effect of Recycled Plastic Aggregate Replacement	Notes
Workability	Increased slump and flowability	Hydrophobic plastic reduces water demand
Compressive Strength	Slight reduction at low replacement (5–10%), significant loss at higher levels	Due to weaker bonding and lower density
Tensile Strength	Minor reduction at low levels, more at higher replacements	Voids and interface debonding
Freeze–Thaw Resistance	Poor, with significant strength loss and brittleness	Thermal expansion mismatch and weak bonding
Density	Decreases with increasing plastic content	Plastic's lower density compared to natural aggregates

Different plastic types influence the long–term durability of concrete mainly through their distinct physical, chemical, and surface properties, which affect bonding with cement, degradation behavior, and mechanical performance. Plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) generally reduce compressive, tensile, and flexural strength as their content increases. This is mainly due to weaker bonding between the hydrophobic, smooth plastic particles and the cement matrix, creating a porous and less cohesive interfacial transition zone, which compromises durability. The optimal replacement proportion remain, therefore, an important factor. In this sense, studies find that low incorporation rates (around 5–15%) of plastic aggregates, particularly plastics like PET or certain polyethylene wastes, can balance sustainability with mechanical performance. Beyond these percentages, durability and strength reductions become more pronounced.

Also, different plastics degrade differently under UV exposure, heat, freeze–thaw cycles, and alkaline cement environments. The long–term chemical interactions and degradation rates differ among plastic types but are not yet fully understood.

5. CONCLUSIONS

In conclusion, recycled plastic aggregates improve concrete workability but tend to reduce durability and strength, especially under freeze–thaw conditions. Optimal performance is typically achieved at low replacement levels (around 5–10%), where workability benefits are maximized and durability losses are minimized. Further research into particle treatment and mix design is needed to enhance durability for wider structural applications.

Key influencing factors in concrete workability and durability when using plastic aggregates include:

- The main workability factors are:
  - Hydrophobic nature of plastic aggregates improves workability by reducing water demand to wet the particles, leading to better fluidity of concrete mixes.
  - Surface shape and texture of plastic flakes affect workability; smooth, semi-spherical plastic particles enhance workability, while angular or non-uniform shaped particles reduce it.
  - Particle size and distribution influence the packing and flow; finer or well-graded plastic aggregates close to natural sand grading can maintain better workability.
  - Water-cement ratio adjustments may be needed as plastic aggregates alter rheology, sometimes requiring less water for fluidity.
  - Mixing time and method also affect incorporation and uniformity of plastic aggregates, impacting workability.
- The main durability factors are:
  - Bonding strength between plastic aggregates and cement paste is weaker than natural aggregates, leading to reduced mechanical strength and increased porosity, which affects durability negatively.

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- Plastic aggregate content: Higher replacement levels (>10-15%) tend to decrease compressive strength and tensile strength due to weaker interfacial transition zones.
- Thermal expansion difference between plastic and cement matrix can cause internal stresses and microcracking, especially under freeze-thaw cycles, reducing durability.
- Plastic particle density and mechanical properties are lower compared to natural aggregates, which can reduce overall concrete density and load-bearing capacity.
- Moisture absorption: Plastic aggregates being hydrophobic can create moisture variation within concrete, affecting freeze-thaw resistance and possibly leading to brittleness.
- Surface roughness of plastic aggregates improves mechanical interlock, enhancing strength and durability compared to smooth plastic surfaces.
- Curing conditions influence plastic aggregate concrete performance less than plastic content and mix quality.

In summary, the workability of plastic-aggregate concrete improves with smooth, well-sized plastic flakes and appropriate water content adjustments. Durability is mainly influenced by the weakened bond at the interface, plastic content, and thermal-mechanical incompatibility, which must be mitigated through careful material selection and mix design.

The successful incorporation of recycled plastic aggregates in concrete requires careful consideration of several critical factors that significantly influence the workability of fresh concrete. These factors must be understood and properly managed to achieve optimal mixing, placing, and finishing properties. To maximize both workability and durability the following optimization strategies and activities are needed:

- gradation control: optimize particle size distribution to minimize void content;
- mix design adjustment: increase cement content and adjust water–cement ratio to compensate for reduced bonding;
- admixture use: employ plasticizers and air–entraining agents as needed;
- quality control: ensure uniform distribution and proper consolidation.

Proper mixing procedures become critical with plastic aggregates:

- extended mixing times may be required for uniform distribution;
- mixing sequence optimization to prevent plastic aggregate floating or segregation;
- admixture compatibility considerations for maintaining workability over time.

The successful incorporation of recycled plastic aggregates in concrete requires careful consideration of these key factors, with particular attention to the balance between environmental benefits and performance requirements. In fact, the successful incorporation of recycled plastic aggregates requires understanding these interconnected factors and their cumulative effects on fresh concrete behavior. Proper management of particle characteristics, replacement percentages, and mixing procedures enables the achievement of satisfactory workability while maintaining concrete performance standards. While challenges exist, proper understanding and application of these principles can lead to sustainable concrete solutions with acceptable engineering properties.

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