YOKOHAMA NATIONAL UNIVERSITY

Development of Eco-Friendly Controlled Low-Strength Material Utilizing Fresh Concrete Waste and By-products

(生コンクリートの廃棄物や副産物を活用した環境負荷低減型のCLSMの開発)

A dissertation submitted in partial fulfillment of the requirements for the degree of Master of Engineering in Civil Engineering

By

HATEU EBSA BERHANU

23RB917

Academic Supervisor

Professor Dr. Akira HOSODA

Co-supervisors

Prof. Dr. Chikako FUJIYAMA

Assoc. Prof. Dr. Satoshi KOMATSU

Yokohama, Japan

July 2025

DEDICATION

I dedicate all my success to my parents, especially my mother, whose unwavering encouragement, prayers, and belief in my dreams have guided and supported me throughout this journey.

ACKNOWLEDGMENTS

First and foremost, I would like to extend my gratitude and praise to Almighty God and Jesus Christ for providing me with the strength and comfort to complete this research.

I also want to extend my deepest gratitude to my academic advisor, Professor Dr. Akira Hosoda, for his invaluable advice, continuous guidance, unwavering support, constructive discussions, and constant encouragement throughout this study. It has been a pleasure working with him.

I am also sincerely grateful to my co-advisors, Professor Dr. Chikako Fujiyama and Associate Professor Dr. Satoshi Komatsu, for their invaluable guidance and constructive feedback throughout this work. Completing this work would not have been possible without the tireless guidance and support of Professor Dr. Chikako Fujiyama.

I would like to extend my heartfelt appreciation to Nagaoka Ready-Mixed Concrete Co., Ltd., for their financial support, which made this study possible. A special thank you to the company president, Mr. Mitsuya Miyamoto, for facilitating all necessary arrangements, providing access to the company's resources, and for his generous support in enabling me to conduct my experiments.

I am equally grateful to Mr. Ikegami, the Manager of Nagaoka Ready-Mixed Concrete Co., Ltd., and to all the laboratory technicians at Izu Chuo LLP for their assistance and services whenever needed.

I would also like to express my sincere thanks to the Ministry of Education, Culture, Sports, Science, and Technology of Japan (MEXT) for awarding me a research scholarship.

Finally, I dedicate all my success to my beloved mom, whose prayers, unconditional love, care, and constant encouragement have inspired me to pursue my educational dreams through thick and thin.

TABLE OF CONTENTS

DEDICATION I

ACKNOWLEDGMENTS II

TABLE OF CONTENTS III

LIST OF FIGURES VIII

LIST OF TABLES X

LIST OF ABBREVIATIONS XII

ABSTRACT XIII

CHAPTER 1: INTRODUCTION 1

1.1. Background of the Study 1

1.2. Statement of the Problem 4

1.3. Objectives of the Study 4

  1.3.1. General Objective 4

  1.3.2. Specific Objectives 4

1.4. Significance of Study 5

1.5. Scope of the Study 6

1.6. Limitations of the Study 6

1.7. Organization of the Thesis 7

CHAPTER 2: LITERATURE REVIEW 8

2.1. Introduction 8

2.2. Historical Background 8

2.3. Materials Used in CLSM Mixtures 9

  2.3.1. Binder Materials 10

  2.3.2. Aggregates 11

  2.3.3. Mixing Water 12

  2.3.4. Admixtures and Additives 13

2.4. Mixture Proportioning 14
2.5. Properties of CLSM 16
  2.5.1. Fresh CLSM Properties...16
  2.5.2. Hardened CLSM Properties 17
  2.5.3. Durability and Environmental Issues Related to CLSM..19
2.6. Particle Size Distribution of IWA Fine Aggregate 21
2.7. CLSM Application in Utility Trench Backfilling 22
  2.7.1. Backfill Around Buried Pipes 23
  2.7.2. Conduit Bedding 24
2.8. Standard Guideline and Specifications of CLSM 25
  2.8.1. American Concrete Institute (ACI) Guideline 25
  2.8.2. Technical Manual of Fluidized Soil in Japan 27
2.9. Testing Standard for CLSM 29
2.10. Advantages of Controlled Low-Strength Materials 32
2.11. Challenges and Limitations of Controlled Low-Strength Materials.....................33
CHAPTER 3: EXPERIMENTAL METHODOLOGY 35
3.1. Introduction..35
3.2. Materials Properties 35
  3.2.1. Ground Granulated Blast Furnace Slag (GGBFS) 36
  3.2.2. Improved Water Absorption (IWA) Fine Aggregate 36
  3.2.3. Concrete Sludge Powder (CSP) 38
  3.2.4. Supernatant Water 41
  3.2.5. Super Retardant Admixtures and Additives 42
3.3. Experimental Procedure and Mix Proportions..43
  3.3.1. Stage-I: Optimization of Aggregate Content...45
  3.3.2. Stage-II: Partial Replacement by Concrete Sludge Powder...................................46

3.3.3. Stage-III: Optimization of Binder Content 47

3.3.4. Stage IV: Optimization of Admixtures and Additions 48

3.4. Specimen Preparation and Test Methods 49

3.4.1. Fresh CLSM Test Methods 49

3.4.2. Hardened CLSM Test Methods...51

3.4.3. Durability Test Methods..53

3.5. Gradation Formulation of IWA Fine Aggregate in CLSM Mixtures 55

3.6. Summary..56

CHAPTER 4: EXPERIMENTAL STUDY RESULTS AND DISCUSSION 57

4.1. Introduction..57

4.2. Stage-I: Optimization of Aggregate Content 57

4.3. Stage-II: Partial Replacement by Concrete Sludge Powder 58

4.4. Stage-III: Optimization of Binder Content 59

4.5. Stage-IV: Optimization of Admixtures and Additions..64

4.6. Durability of Eco-friendly CLSM..65

4.6.1. Hexavalent Chromium Leaching Test...65

4.6.2. Performances after Wetting and Drying Cycles..66

4.7. Effect of IWA Fine Aggregate Gradation Zones on Eco-friendly CLSM Properties.......68

4.7.1. Effect of IWA Fine Aggregate Gradation Zones on Fresh Properties.......................68

4.7.2. Effect of IWA Fine Aggregate Gradation Zones on Compressive Strength..............70

4.8. Eco-friendly CLSM Scanning Electron Microscopy Observation 72

4.9. Summary..73

CHAPTER 5: LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING..............74

5.1. Introduction..74

5.2. Materials 76

5.2.1. Eco-Friendly CLSM..76

5.2.2. Conventional CLSM 77

5.2.3. Compacted Granular Compacted Fill...78

5.2.4. Trench Cross-Section Details for Utility Buried Pipes 79

5.3. Life Cycle Assessment (LCA) 80

5.3.1. Goal and Scope Definition 81

5.3.2. Life Cycle Inventory (LCI) 85

5.3.3. Life Cycle Impact Assessment (LCIA) 86

5.3.4. Interpretation 87

5.4. Life Cycle Costing (LCC)..88

5.4.1. Direct Costs (DC)..89

5.4.2. Indirect Costs (IC)..89

5.4.3. Rate Analysis for Direct Cost..89

5.5. Summary 90

CHAPTER 6: LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING RESULT AND DISCUSSION 91

6.1. Introduction...91

6.2. Life Cycle Assessment Result...91

6.2.1. Global Warming 91

6.2.2. Mineral Resource Scarcity 93

6.2.3. Fossil Resource Scarcity 93

6.2.4. Ozone Formation...94

6.2.5. Fine Particulate Matter Formation 94

6.2.6. Terrestrial Acidification..95

6.3. Life Cycle Cost Analysis Result 96

6.4. Summary 99

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS 100

7.1. Conclusion 100

7.1.1. Development of Optimized, Excavatable, and Eco-friendly CLSM........................ 100

7.1.2. Life Cycle Assessment and Life Cycle Costing.. 101

7.2. Recommendation for future works 101

7.3. Summary.. 103

REFERENCES.. 104

APPENDIX A: HEXAVALENT CHROMIUM DETECTION TEST RESULT 114

APPENDIX B: EMISSION INVENTORY DATA 115

APPENDIX C: LIFE CYCLE COSTING (LCC) ANALYSIS 116

LIST OF FIGURES

Figure 1.1 *Current management of processing wastes in RMC plants* 3

Figure 2.1 *General methodology for the design of optimized CLSM* 15

Figure 2.2 *IWA fine aggregate gradation zone in fluidized soil* 21

Figure 2.3 *Country-wise analysis of articles published related to CLSM* 22

Figure 2.4 *Underground utilities trench cross-section* 24

Figure 3.1 *GGBFS Shapes* 36

Figure 3.2 *Particle size distribution of materials used in this study* 37

Figure 3.3 *IWA fine aggregate shapes* 38

Figure 3.4 *Production stages of IWA aggregates* 38

Figure 3.5 *Production stages of concrete sludge powder* 39

Figure 3.6 *Concrete sludge powder (CSP) shapes* 39

Figure 3.7 *Treatment stages of supernatant water* 42

Figure 3.8 *Geoliter 10 admixture, its density and color pigment* 43

Figure 3.9 *General methodology for the mix design optimization* 45

Figure 3.10 *List of experiments conducted on fresh CLSM properties* 51

Figure 3.11 *List of experiments conducted on hardened CLSM properties* 53

Figure 3.12 *Wetting-drying cycles* 54

Figure 3.13 *IWA fine aggregate gradation analysis* 55

Figure 3.14 *List of experiments conducted at each grading zone (Center)* 55

Figure 3.15 *Unconfined compressive strength at 7-day and 28-day at each grading zone* 56

Figure 4.1 *Water-to-solid ratio effects on the plastic properties of eco-friendly CLSM* 58

Figure 4.2 *Filler-to-aggregate ratio effects on the plastic properties of eco-friendly CLSM*. 58

Figure 4.3 *Filler-to-aggregate ratio effects on the unconfined compressive strength* 59

Figure 4.4 *Binder content effects on the plastic properties of eco-friendly CLSM mixtures* .. 60

Figure 4.5 *Binder content effects on the unconfined compressive strength* 61

Figure 4.6 *Removability modulus*..62

Figure 4.7 *Needle penetration and permeability test results* 63

Figure 4.8 *Geoliter -10 content effects on the plastic properties of eco-friendly CLSM*........64

Figure 4.9 *Color intensity of eco-friendly CLSM*...65

Figure 4.10 *Geoliter 10 admixture effects on hardening time* 65

Figure 4.11 *Variation of initial and residual unconfined compressive strength*.....................68

Figure 4.12 *Effect of Gradation Zone on the Unconfined Compressive Strength*.................70

Figure 4.13 *IWA fine aggregate gradation zone in eco-friendly CLSM*................................71

Figure 4.14 *Eco-friendly CLSM SEM observation* 73

Figure 5.1 *The four types of trenches considered in the analysis* 75

Figure 5.2 *Trench cross-section details*...80

Figure 5.3 *System boundary of the scenarios considered for eco-friendly CLSM*.................82

Figure 5.4 *System boundary of the scenarios considered for conventional CLSM* 82

Figure 5.5 *System boundary of the scenarios considered for granular compacted backfill*..82

Figure 5.6 *The model graph for the excavation stage of conventional CLSM*.......................86

Figure 5.7 *The model graph for the extraction to installation stages of conventional CLSM*86

Figure 5.8 *The model graph for the extraction to installation stages of eco-friendly CLSM*.87

Figure 5.9 *The model graph for the excavation stage of granular compacted fill* 87

Figure 5.10 *The model graph for the extraction to installation stages of compacted fill*.......87

Figure 6.1 *Comparison of global warming, mineral, and fossil resource scarcity*................91

Figure 6.2 *Comparison of ozone formation, fine PM2.5 and terrestrial acidification*...........94

Figure 6.3 *Unit price comparison for each stage of the LCC*...97

Figure 6.4 *Total price comparison for each stage of the LCC*...98

LIST OF TABLES

Table 2.1 *The American Public Works Association utility color code 14*

Table 2.2 *Environmental quality standards for soil 20*

Table 2.3 *The criteria requirements for different CLSM applications 26*

Table 2.4 *Target values for application to the liquefied stabilized soil 28*

Table 2.5 *Test methods for the determination of CLSM mixtures as per ACI guidelines 30*

Table 2.6 *Test methods for the determination of fluidized soil mixtures 31*

Table 2.7 *Cited Advantages of CLSM (ACI 299R-13) 32*

Table 3.1 *The basic physical properties of the IWA fine aggregate 37*

Table 3.2 *Chemical composition of materials used in this study 40*

Table 3.3 *Quality of non-tap waters standard for supernatant water 41*

Table 3.4 *General criteria for CLSM application and target performance in this study 44*

Table 3.5 *Mixture proportions of Stage-I 46*

Table 3.6 *Mixture proportions of Stage-II 47*

Table 3.7 *Extra supernatant water demand adjustment before Stage-III 47*

Table 3.8 *Mixture proportions of Stage-III 48*

Table 3.9 *Mixture proportions of Stage-IV 49*

Table 3.10 *Effects of particle size distribution of the IWA fine aggregates 56*

Table 4.1 *Comparison of the leaching test for CLSM with different binders 66*

Table 4.2 *Mass losses in wet-dry durability testing for eco-friendly CLSM 67*

Table 4.3 *Effects of particle size distribution of the IWA fine aggregate 69*

Table 5.1 *Eco-friendly CLSM mix proportions 77*

Table 5.2 *Conventional CLSM mix proportions 78*

Table 5.3 *Granular compacted backfill mix proportions 79*

Table 5.4 *Physical properties of the granular materials used in this study 79*

Table 5.5 *Parameters, options, and their description are considered in the study 83*

Table 5.6 *Location and actual transport distance between source, plant, and project site.....84*

Table 5.7 *Types of equipment considered and their respective emission inventory data.........85*

Table 6.1 *Stages contribution in global warming, fossil and mineral resource scarcity.........92*

Table 6.2 *Stages contribution in ozone formation, fine PM2.5 and terrestrial acidification..95*

Table 6.3 *Contribution of each LCC phase to the unit and total price per linear trench........99*

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AEA	Air-Entraining Admixtures
APWA	American Public Works Association
ASTM	American Society for Testing and Materials
BEDEC	Database of Construction Elements
BFS	Blast Furnace Slag
CCU	Carbon Capture Utilization
CDF	Controlled Density Fill
CLSM	Controlled Low-Strength Material
Cr(III)	Trivalent Chromium
Cr(VI)	Hexavalent Chromium
CS	Classical Solution
CS + R	Classical Solution with Reuse
CSP	Concrete Sludge Powder
CSW	Concrete Slurry Waste
C&D	Construction and Demolition
ECO	Eco-trench
FEM	Finite Element Method
FM	Fineness Modulus
GGBFS	Ground Granulated Blast Furnace Slag
GPOC	Granulated Porous Concrete
HCFA	High-Calcium Fly Ash
IBA	Incineration Bottom Ash
ICP	Induction-Coupled Plasma
ISO	International Organization for Standardization
ITeC	Construction Technology Institute of Catalonia
IWA	Improved Water Absorption
JHS	Japan Highway Public Corporation Standard
JIS	Japan Industrial Standard
JSCE	Japan Society of Civil Engineers
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LL	Lower Limit
NRMCA	National Ready Mixed Concrete Association
OPC	Ordinary Portland Cement
PSD	Particle Size Distribution
PWRI	Public Works Research Institute
RC	Returned Concrete
RCA	Recycled Concrete Aggregate
RE	Removability Modulus
RMC	Ready-Mixed Concrete
SCM	Supplementary Cementitious Materials
SEM	Scanning electron microscopy
SPD	Standard Proctor Density
UCS	Unconfined Compressive Strength
UL	Upper Limit

ABSTRACT

Rapid industrialization and urbanization in recent decades have posed significant challenges to the natural environment, resulting in a substantial increase in waste production. Ready-mixed concrete (RMC) manufacturers confront the dual challenges of managing returned concrete and the water needed for cleaning delivery trucks, along with disposing of waste generated during the washing process. Given the need for sustainable development, an increasing number of recycled waste materials and industrial by-products have been utilized for the creation of sustainable, eco-friendly, controlled low-strength materials (CLSM). Nonetheless, the development of cementless excavatable eco-friendly CLSM that utilizes returned fresh concrete waste materials, along with its economic and environmental benefits and impact, remains insufficiently investigated and quantified.

The present study thoroughly examined the development of eco-friendly CLSM in backfilling applications for buried pipes, utilizing entirely recycled concrete waste and industrial by-products. The durability of the optimal eco-friendly CLSM, alongside a comprehensive analysis of its economic and environmental impacts, was compared to conventional CLSM and granular compacted fill using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) across six impact categories. This study employed a four-stage experimental approach that included optimizing aggregate content, partially replacing Improved Water Absorption (IWA) fine aggregate with concrete sludge powder (CSP), determining the ideal ground granulated blast furnace slag (GGBFS) binder content, and exploring the effects of the retardant admixture geoliter 10.

Experimental results indicate that incorporating up to 20% CSP improves the stability of the eco-friendly CLSM mix by reducing bleeding and increasing its unconfined compressive strength. A GGBFS binder content of 40 kg/m^3 was found to be optimal, achieving the criterion of re-excitability with a 28-day unconfined compressive strength of 281.90 kN/m^2, a Removability Modulus of 0.67, and long-term strength below the limit. Geoliter 10 effectively delayed hardening and enhanced workability. The water permeability values of the eco-friendly mix decreased as the unconfined compressive strength increased. Importantly, hexavalent chromium leaching remained well within regulatory limits at 0.007 mg/L, which complies with environmental quality standards for soil, demonstrating the effectiveness of GGBFS in minimizing leaching. The study also found that the durability test of the optimal eco-friendly

CLSM, subjected to twelve wetting and drying cycles, showed high resistance to degradation, which directly correlates with its compressive strength. The results of the LCA and LCC analysis indicate that eco-friendly CLSM is the most sustainable alternative across all six impact categories, while granular compacted fill materials are the least efficient. Compared to granular compacted fill and conventional CLSM, eco-friendly CLSM can significantly reduce the total life cycle cost of backfilling per linear meter of trench, achieving savings of 53% and 22.6%, respectively.

The findings can provide policymakers with key information to better understand the environmental benefits of using recycled materials in eco-friendly concrete production, as well as support the development of policies for managing returned concrete and implementing zero-waste initiatives at RMC batching plants. This research successfully demonstrates the feasibility of producing optimized, excavatable, and eco-friendly CLSM entirely from recycled concrete waste and industrial by-products, contributing to sustainable construction by promoting waste minimization, resource efficiency, and circular economy principles.

CHAPTER 1: INTRODUCTION

1.1. Background of the Study

The growing need for new infrastructure, driven by fast urbanization and increasing populations, raises concerns about the environmental effects of the construction industry. These effects include the utilization of scarce resources, the generation of a substantial amount of construction and demolition waste, and the consumption of a considerable amount of energy. This situation emphasizes the need to look for eco-friendly options [1]. The growing worldwide need for concrete, which is around 25 billion tons each year, creates a lot of construction and demolition waste, including returned fresh concrete [2, 3]. Depending on quality assurance in concrete production or construction, a small percentage of the total output, often during peak construction periods, can increase waste to as much as 5-9% of total concrete production, amounting to approximately 125 million tons of global waste. [3, 4]. This waste presents an increasing environmental challenge, worsened by inadequate disposal practices. It leads to overflowing landfills and possible contamination, which must be mitigated through sustainable recycling and reuse approaches [4, 5].

Using virgin aggregates in concrete production leads to resource depletion and habitat destruction. In Japan, Construction and Demolition (C&D) waste accounts for a large portion of industrial waste. Estimates suggest it reaches up to 77 million tons each year [6, 7]. Meanwhile, disposing of C&D waste, mainly concrete, fills landfills and poses significant environmental risks [8]. This unsustainable cycle requires new solutions that lower our reliance on new materials and promote recycling and reuse. Also, managing waste from ready-mixed concrete plants presents challenges, like low reuse rates and the need for an effective treatment method [5].

As sustainable construction is now a priority in most parts of the world, the sustainable management of processing waste from ready-mixed concrete (RMC) production has become a concern. Concrete producers and researchers are now investing greater effort into the scientific and technical aspects focused on waste management in concrete batching plants to reduce its production and disposal, while promoting recycling and reuse [3, 9-11]. The management of returned fresh concrete poses a significant challenge in Japan, often involving a multi-stage process. In recent decades, the washing-out system has become more common at RMC plants.

However, such systems require substantial capital investment, careful operational management, and are currently limited by environmental impact and complexity [4].

Recently, another technique for transforming returned concrete waste into granular materials has been developed, as reported by Ferrari et al. [4] in this process, fresh concrete waste is remixed with accelerating additives, transforming it into a granular material within minutes. The improved water absorption (IWA) system offers a more sustainable and efficient method for recovering returned concrete. It involves adding a special mix directly into mixer trucks and using high-speed stirring to bond the cement paste or mortar to aggregates. This process forms new, usable aggregates. Compared to traditional washing methods, the IWA system significantly reduces sludge water, dehydrated cake, and concrete chunks. This results in less waste. This approach supports broader initiatives to utilize industrial by-products and fresh concrete waste better, promoting more sustainable construction practices [12]. It supports a circular economy in the construction industry [13].

Additionally, RMC uses an impact crusher to make Concrete Sludge Powder (CSP) from reclaimed and dewatered Concrete Slurry Waste (CSW). This waste is a mix of fine aggregates, cement hydration products, and leftover cement particles collected from sedimentation pits [5]. CSP is a byproduct of making and recycling concrete. It has significant potential for sustainable construction. CSP comes from the CSW created during concrete mixing, cleaning trucks and equipment, or recycling concrete. Unfortunately, CSP often ends up in landfills [14]. However, since it mainly consists of cement paste, fine aggregates, and possibly additives, it has the potential to be a valuable resource [15]. The changing composition of CSP, which depends on the original concrete mix and processing methods, makes it hard to achieve consistent performance [16]. The possible presence of heavy metals and other harmful substances raises environmental concerns. This requires careful handling and treatment [17].

Supernatant water, the clear liquid separated from concrete washout or sludge, provides an alternative method for recovering resources in concrete production. This water is often discarded as wastewater, but it contains leftover cement particles, fine aggregates, and chemical additives [17]. Factors such as pH levels, dissolved solids, and specific admixtures require assessment. Understanding these factors and applying appropriate treatment methods when necessary can transform supernatant water from waste into a valuable resource [5].

The American Concrete Institute (ACI) 229 committee defined Controlled Low-Strength Material (CLSM) as self-compacting cementitious backfill materials [18]. It works well for backfill, utility bedding, void fill, and bridge approaches [19]. A key feature of CLSM technology is its ability to handle different products and waste materials both safely and effectively [20]. A practical way to utilize recycled fresh concrete waste and industrial by-products is to incorporate them into creating CLSM. Developing eco-friendly CLSM mixes meets the rising demand for sustainable construction materials and supports the principles of a circular economy in the construction industry. The existing waste management strategies for all types of waste generated from the RMC industry are illustrated in **Figure 1.1**.

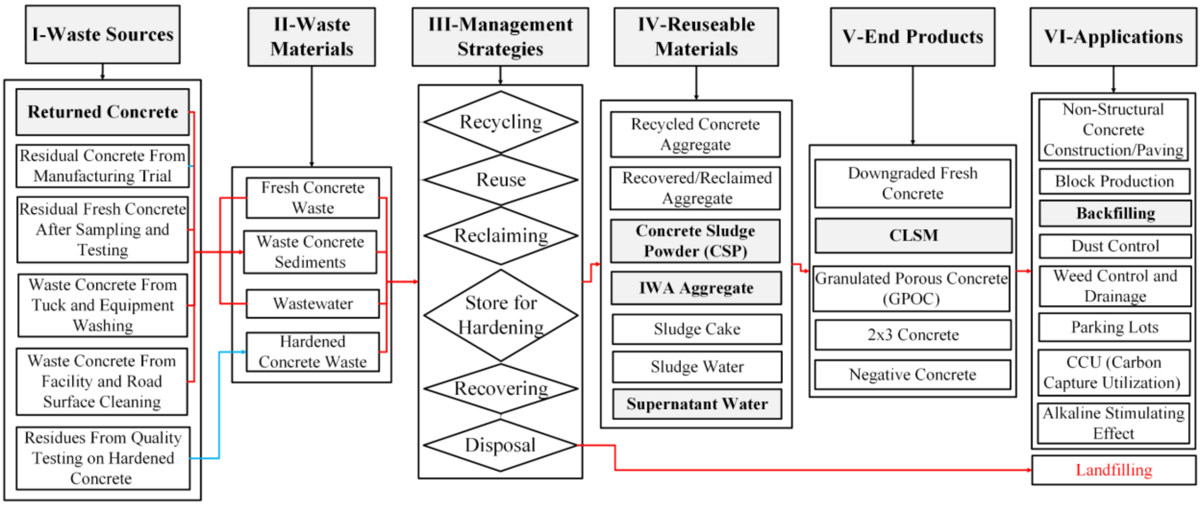


Figure 1.1 Current management of processing wastes in RMC plants

Previous research has explored the potential of recycled concrete aggregates (RCA) in CLSM as a sustainable alternative to natural aggregates [19, 21], reducing landfill burden and conserving natural resources [22]. Studies have also shown the successful use of returned concrete with non-toxic chemical additives as a fine aggregate in fluidized soil and as a partial cement replacement, yielding promising strength results. However, the full potential of fresh returned concrete waste in CLSM remains relatively unexplored.

This study addresses this gap by optimizing an eco-friendly CLSM mix design that utilizes fully recycled fresh returned concrete waste, including IWA fine aggregate, CSP, and supernatant water, as well as industrial by-products, specifically for the backfilling of buried pipes. The research encompasses a four-stage experimental investigation to evaluate both fresh and hardened properties of the CLSM mixtures, ensuring optimal material utilization and sustainable construction practices. The utilization of industrial by-products further enhances the sustainability of this approach [12] and addresses the growing need for effective management of both industrial and construction waste [23]. Furthermore, the study seeks to improve the understanding of the long-term performance and durability of CLSM incorporating these recycled components, particularly in underground applications where re-excavation may be necessary [24].

The ACI Committee 229 document, ACI 229R-13, serves as the primary guideline for CLSM in the United States and has been extensively referenced globally [18, 25]. In Japan, liquefied soil stabilization methods have been widely adopted in various construction projects, enabling the effective reuse of geotechnical materials generated during the construction process. The "*Technical Manual for Fluidized Soils*", a key Japanese technical manual, incorporates advancements in fluidized soil technology, and its principles can be applied to CLSM due to the similarities between the two materials [26].

1.2. Statement of the Problem

Conventional CLSM production relies on natural resources, such as aggregates and Portland cement. Extracting and processing these materials harms the environment. This harm encompasses habitat destruction, resource depletion, and the release of greenhouse gases. The construction industry also generates a significant amount of waste. The returned fresh concrete causes environmental and economic issues. This research investigates methods to reduce the environmental impact of CLSM production and concrete waste disposal by utilizing industrial byproducts and fresh concrete waste as sustainable alternatives in CLSM mixes. The study specifically aims to create an eco-friendly CLSM for filling buried pipes. This approach presents a significant opportunity for reusing materials and minimizing waste. The research seeks to determine the optimal mix designs using these alternative materials, while ensuring that the CLSM meets the performance standards required for its intended use.

1.3. Objectives of the Study

1.3.1. General Objective

The main objective of this research is to develop an optimized, excavatable, and eco-friendly CLSM for utility trench backfilling, utilizing fresh returned concrete waste and industrial by-product material.

1.3.2. Specific Objectives

The primary specific objectives of this study are:

- To explore the feasibility of using concrete sludge powder from sludge cake to produce eco-friendly CLSM.
- To determine the effects of using a super retardant on the workability of CLSM.
- To investigate the effects of IWA fine aggregate particle size distribution (PSD) on the properties of CLSM mixes.
- To investigate the effect of wetting-drying cycles on the durability of CLSM in terms of mass loss and unconfined compressive strength (UCS)
- To compare and assess the environmental impacts and economic aspects of eco-friendly CLSM in comparison with conventional CLSM and granular compacted backfilling using life cycle assessment (LCA) and life cycle costing (LCC) tools.
- To compare and verify the properties of CLSM with the standards outlined in ACI 229R-13 and the Public Works Research Institute (PWRI) *Technical Manual for Fluidized Soil*.

1.4. Significance of Study

The findings of this study are expected to make a significant contribution to utility trench backfilling for buried pipes. First, the study aims to improve understanding of the properties and in-trench performance of CLSM backfilling materials. This will provide engineers and project planners with the essential data needed to make informed decisions. Second, it introduces a new, environmentally friendly, and cost-effective alternative for trench backfilling. This approach aligns sustainability goals while maintaining efficient construction.

Additionally, by examining the fresh, hardened, and durability properties of CLSM backfilling materials under different conditions and factors, the study offers insights into their long-term performance and durability. The research also aims to create a reliable decision support system to assist stakeholders in effectively planning and scheduling utility trench backfilling projects. Beyond its technical contributions, the study serves as a valuable resource for utility owners and municipalities. It enables them to create detailed standards, define performance limits, and set clear acceptance criteria for backfilling operations. The findings can inform future research and development in this area, particularly regarding the optimization of mix design for sustainable CLSM, as well as environmental and economic comparisons.

1.5. Scope of the Study

The scope of this dissertation includes:

- A comprehensive literature review on the properties, applications, materials, guidelines, and test methods used for CLSM
- Experimental investigation of the fresh and hardened properties of eco-friendly CLSM incorporating GGBFS, IWA fine aggregate, CSP, and supernatant water.
- Durability test to investigate hexavalent chromium leaching effects and resistance of eco-friendly CLSM subjected to wetting-drying cycles.
- Comparative analysis of economic and environmental impacts of eco-friendly CLSM with conventional CLSM and granular compacted fill based on LCA and LCC analysis.
- Recommendations for the practical application of eco-friendly CLSM in construction and suggestions for future research.

1.6. Limitations of the Study

The limitations of this study include:

- The availability and properties of returned concrete waste materials can vary based on the recycling method, type, and quality of the returned concrete, which may limit the generalizability of the findings.
- Due to uncontrolled material properties, a comprehensive investigation into the effects of the physical and chemical properties of materials on CLSM properties, rather than on the impact of IWA fine aggregate gradation, was not conducted.
- Due to the complexity of RC comprehensive microstructural characterization utilizing techniques such as rheology, microscopy, and non-destructive testing, and also the amount of alkalis contributed from returned concrete materials using Induction-Coupled Plasma (ICP), has not been investigated.
- Due to a lack of specific test methods, guidelines, and standards, a modified test method for experimental testing of concrete was utilized.
- Due to a lack of commercial databases, the study utilizes emission inventory data from construction companies and from previously published articles.
- The findings may not be directly applicable to other CLSM applications without further investigation, as each specification has its own respective requirements.

1.7. Organization of the Thesis

This thesis is organized into the following chapters:

Chapter 1: Introduction - This chapter provides an overview of the research, including the general background, objectives, problem statement, significance, limitations, scope, and organization of the thesis.

Chapter 2: Literature Review - This chapter summarizes the latest developments and current practices related to CLSM. It discusses typical applications, benefits, and challenges of CLSM, including case histories. The chapter also covers fresh and hardened properties, test methods, and constituent materials of CLSM in detail. Additionally, it addresses CLSM specifications, quality assurance, and quality control.

Chapter 3: Experimental Methodology - This chapter describes the experimental program of the study. It includes details about the CLSM mixtures used in the four stages, as well as the material characteristics of the constituent materials. Additionally, it covers the testing methods and standards used to evaluate various factors.

Chapter 4: Experimental Study Results and Discussion - This chapter presents the results and discussion of a four-stage experimental program, focusing on fresh and hardened properties, durability, and the effects of IWA fine gradation zones.

Chapter 5: Life Cycle Assessment and Life Cycle Costing - This chapter discusses the methodology used to assess the economic and environmental impacts of three backfilling materials through life cycle costing (LCC) and life cycle assessment (LCA).

Chapter 6: Life Cycle Assessment and Life Cycle Costing Results and Discussion - This chapter presents the results and discussion of life cycle assessment and life cycle cost comparative analysis results, focusing on eco-friendly CLSM, conventional CLSM, and granular backfill across six environmental impact categories and direct cost analysis. The findings are examined within the context of existing literature.

Chapter 7: Conclusion and Recommendations - This chapter summarizes the key findings of the study, discusses the implications for sustainable construction, and provides suggestions for future studies.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Controlled low-strength material (CLSM) is a self-compacting, cementing material, often utilized as a backfill, providing an alternative to traditional compacted fill methods [18]. The American Concrete Institute (ACI) founded Committee 229, which reports on CLSM applications, developments, material properties, mix proportioning, and construction and quality control procedures. [27]. The ACI Committee defined the upper limit of unconfined compressive strength (UCS) of CLSM at 28 days as 8.3 MPa [18]. CLSM typically consists of ordinary Portland cement (OPC), fine aggregates, supplementary cementing materials (SCM), and water. The primary application of CLSM is as structural fill and backfill in place of compacted soil [18].

CLSM has been described using several terms, such as controlled density fill (CDF), controlled pavement base, controlled structural fill, controlled thermal fill, flowable fill, unshrinkable fill, flowable mortar, flowable fly ash, fly ash slurry, fly ash fill, flowable grout, plastic soil cement, soil cement slurry, anti-corrosion fill, one-sack mix, and also commercial names such as K-Krete, M-Crete, and S-Crete [19, 27, 28]. However, the ACI Committee 229 has consistently adopted the term CLSM to refer to this material [18].

2.2. Historical Background

Differential settlement between trench backfills and surrounding materials is a common issue during new construction, when replacing or repairing cross-drains in older buildings, and in utility openings in existing structures. This issue usually occurs due to inadequate compaction of trench backfill materials. It is most often seen where utility repairs or new utility work happen on existing roads. This can lead to a shallow dip or trench that often runs along the length of the roadway, with some trenches crossing the centerline.

Conventional backfilling for various excavations involves using granular materials. Contractors deposit these soils in thin layers, spreading and compacting them to achieve a specific level of compaction. This process is time-consuming and complicated. Often, contractors do not follow it properly. Improper compaction of backfill materials can cause excessive settlement problems over time [29]. Poor utility trench reinstatement due to excessive settlement resulting from inadequate backfill compaction was reported as a major contributor to the deterioration of urban roads in the United States and Canada [29-31]. Excessive settlement of the reinstated pavement is a common issue. This often happens because of poor compaction of the soil backfill. Several municipalities have investigated CLSM as a solution to this utility trench problem. This investigation started with the early work done by Metropolitan Toronto in 1985 [32].

The earliest recorded instances of using soil-cement slurry date back to the 1960s; however, it was not until the early 1970s that CLSM use became more widespread [33-35]. During the Enrico Fermi II Nuclear Station project in Monroe, Michigan, engineers from Detroit Edison and Kuhlman Corporation investigated the potential of fly ash in concrete to maximize its usage. Detroit Edison aimed to decrease its fly ash stockpile by increasing its incorporation, while Kuhlman sought to boost production of their ready-mixed concrete trucks. These dual objectives led to initial research on low-strength concrete materials. William E. Brewer of Kuhlman and Frank Zimmer of Detroit Edison hired Edwin L. Saxer from the University of Toledo to conduct laboratory tests to verify that low-strength concretes could be produced while still retaining acceptable quality control.

After successful laboratory tests, Kuhlman Corporation and Detroit Edison Company agreed to fund the creation of K-Krete Inc. The low-strength materials tested, called K-Krete®, were granted trademark rights. Detroit Edison required that the mixtures and their applications be protected before establishing the new company, leading to the development of patents. Four patent categories were identified: mixture design, backfill technique, pipe bedding, and dike construction [36]. Currently, they are allocated to the National Ready Mixed Concrete Association (NRMCA) for general use, enabling RMC producers and contractors to utilize materials similar to K-Krete without risk of legal repercussions [33, 36].

The term-controlled density fill (CDF) was created to bypass the patent on K-Krete backfills, offering the construction industry an alternative low-strength fill for pavement bases, structural, and thermal fills. These early CDF mixes had lower strength than concrete and maintained uniform density in trenches. They can be designed to meet specific density and strength needs. Initially, CDF mixtures had 28-day strengths of about 0.7 MPa, made from fly ash, OPC, fine aggregates, and water [27, 37].

2.3. Materials Used in CLSM Mixtures

According to the ACI 229R specification, standardized material components can be used for CLSM, but this is not always required [18]. Instead, material selection should be guided by factors such as material availability, the costs of obtaining and producing the material, the intended application, and the desired properties of the CLSM [20]. A key benefit of CLSM is that it can use a variety of locally sourced materials, including industrial by-products [12]. This section reviews the most common materials used in CLSM, which include binders, aggregates, fillers, chemical admixtures, and other by-product materials.

2.3.1. Binder Materials

In CLSM mixtures, the binder is essential because it provides the strength and cohesion needed for the material to perform well. Binders help combine different components using adhesive, cohesive, or physicochemical methods. This ensures that the structure remains intact. The careful choice of a binder is critical. It affects both the performance features and the sustainability of the resulting CLSM composite. Studies have examined various binders, including Portland cement and industrial by-products. The focus has been on improving sustainability, meeting specific strength requirements, and adjusting the material to fit application needs [19, 38].

a) Portland cement

Unlike traditional concrete, CLSM incorporates a significantly reduced amount of cement. The type, quality, and quantity of cement have a significant influence on the compressive strength of CLSM. Typically, CLSM mixes primarily utilize Portland cement, conforming to JIS R 5210, to ensure stability and durability. [39, 40]. Additionally, Portland blast-furnace slag cement, conforming to JIS R 5211, is also employed in CLSM preparation. [41]. In CLSM, the content of cement ranges between 30 and 120 kg/m^3 [18]. The lower content of cement in CLSM helps restrict UCS and reduces the setting time [24]. The selection of cement type and proportion should be carefully evaluated to balance cost considerations without compromising the desired properties and performance of CLSM. Optimizing cement usage can contribute to cost-effective CLSM mixtures while meeting project specifications [19].

b) Ground granulated blast furnace slag

GGBFS has been used as a cementitious material due to its good pozzolanic characteristics, and its activation is often achieved with a reactive agent. GGBFS typically has a high specific surface area; thus, when it reacts with water, the larger contact area facilitates a more extensive hydration reaction, resulting in enhanced compressive strength. In general, slags such as steel slag exhibit a slower reaction rate and longer setting time, as the amount of alite is low. A lower hydration rate means a longer time is required to form calcium hydroxide crystals. The preparation of CLSM using slag has been investigated extensively. Raghavendra and Udayashankar [42] developed mixture proportions for CLSM that contain GGBFS as a binder with cement, thereby reducing the usage of cement to a greater extent.

2.3.2. Aggregates

Aggregates are a significant constituent in CLSM, and those meeting American Society for Testing and Materials (ASTM) C33/ C33 M standards are suitable for CLSM production. Given the low-strength requirements of CLSM, aggregates with low stiffness are generally favored. ACI guidelines also permit the use of non-standard materials, such as industrial by-products and waste resources, as CLSM aggregates. Tansley and Bernard have documented various aggregates successfully used in CLSM, including pea gravel with sand, native sandy soil (more than 10% passing through a 75 μm sieve), ASTM C33/C33 M specified aggregates, and quarry waste products. Utilizing these materials as CLSM aggregates provides environmental and economic benefits, contingent upon thorough testing to ensure their suitability for CLSM.

a) Natural aggregates

Conventional CLSM mixtures usually use natural sand as the primary aggregate. This enhances the material's mechanical properties. Adding aggregates, such as sand and gravel, enhances the strength and stability of CLSM. It allows the mixture to support heavier loads and resist deformation. By reducing void spaces, aggregate particles raise density and decrease the risks of segregation [19].

Naik and Ramme [43] produced CLSM using surface-saturated dry (SSD) natural sand having a fineness modulus of 2.79, meeting the ASTM C33/C33 M requirements, and pea gravel as coarse aggregate. Lachemi et al. [44] investigated both the fresh and hardened properties, addressed durability concerns, compared the performance of various types of CKD, and provided recommendations for suitable mix designs applicable in field settings. In this study, a local natural sand characterized by a bulk specific gravity of 2.73 and a water absorption rate of 1.83% was employed. Wang et al. [45] examined the use of incineration bottom ash (IBA) as a replacement for natural aggregates in CLSM. The study's findings showed that using IBA produced in Taiwan as a substitute for natural aggregates in CLSM is a practical and effective method for employing IBA.

b) Recycled aggregate

Recycled aggregate, the source of recycled fine aggregate, is produced by crushing and processing concrete demolition materials from building teardowns and hardened return concrete using machines like crushers. Since CLSM exhibits re-excavability properties, the long-term strength gain is expected to be minimal.

Khatib, [46] investigated concrete incorporating recycled fine aggregate, found a systematic reduction in long-term strength gain. Achtemichuk et al. [47] utilized both fine and coarse recycled concrete aggregate with slag and high-calcium fly ash (HCFA) as the binder to produce CLSM. The CLSM mix containing slag with recycled concrete aggregate (RCA) exhibited greater strength compared to HCFA with RCA. The coarse RCA CLSM mix was found to be more suitable for structural fill work as it gains more UCS and fine RCA. CLSM is ideal for the re-excavation application as its UCS gain is lower.

Lin et al. [48] investigated CLSM properties incorporating recycled aggregate with water-quenched blast furnace slag as the primary binder. CLSM with recycled aggregates exhibited a reduced bleeding tendency compared to CLSM with natural aggregates, as the recycled aggregate-based CLSM has a faster absorption capability. Funayama et al. [49] Also investigated the utilization of IWA fine aggregate, along with blast furnace slag cement type B, in the development of fluidized soil. The results indicate that IWA fine aggregate can be used to produce fluidized soil with suitable physical properties.

2.3.3. Mixing Water

Several studies indicate that water quality has been a concern in civil engineering construction, and therefore, most specifications require the use of potable water. Depending on the situation and local availability, many types of water that are not safe for drinking can still be used in construction. The literature review revealed that there has been limited research on how water quality impacts the properties of CLSM.

Botton et al. [50] studied the reuse of wastewater generated from washing concrete mixer trucks in the concrete production process, thereby reducing the consumption of drinking water. The authors created concrete with three different compositions: with drinking water alone, with half drinking water and half residual water, and with residual water alone. The results indicate that the concrete made with residual water exhibited the same compressive strength as that made with drinking water. The composition containing 50% residual water demonstrated the most significant strength gains compared to the other mixtures.

Su et al. [51] developed mortars and concrete that replace entirely tap water with wash water collected from the top, middle, and bottom of the settling box. The authors assessed the setting time, compressive strength, and flow spread of the mortars, as well as the slump and compressive strength of the concretes. The findings showed that concrete mixed with bottom wash water had a shorter setting time and lower flowability due to the residual cement in the water.

2.3.4. Admixtures and Additives

Admixtures improve the properties and performance of CLSM. Understanding the functions of various additives is crucial for achieving optimal results with CLSM. Common admixtures, such as plasticizers, superplasticizers, and viscosity modifiers, enhance material properties [18].

Blanco et al. [52] investigated the impact of the plasticizer Pozzolith 475N on the consistency and workability of CLSM. In CLSM, the low cement content, combined with the high water volume, should significantly decrease the chances of particle interaction flocculation. The study also revealed that using plasticizers to enhance workability was ineffective for this material, which has a low cement content.

Funayama et al. [49] utilized Floric T, a retardant for concrete, at a concentration of 0.3% of the blast furnace cement type B content (100 kg/m^3), to transport the fluidized soil from the RMC batching plant to the site and investigate its effects on workability and retarding properties. The study results showed that no flow loss occurred when the retarder was added, indicating its effectiveness in delaying hardening for the fluidized soil.

Another essential additive for CLSM is color pigments, which enable the use of colored CLSM in utility line backfilling. The strength of the color is directly related to the dosage amount of pigment used, typically measured in pounds of color additive per cubic meter of cement. Color variations can occur depending on the pigment manufacturer, and liquid-dispensing systems will require different amounts. The utilization of colored CLSM enhances worker safety by eliminating the need for trench entry during compaction, thereby reducing the risk of trench accidents and collapses.

Hospodarova et al. [53] investigated the effects of color pigments on the physical and mechanical properties of concrete compared to reference samples without color pigments. The results showed that the pigments lowered bulk density, slightly increased water absorbability by 1%, and boosted compressive strength by up to 20%. Based on the obtained results, the use of colored pigments in concrete does not negatively impact the physical and strength characteristics of hardened concrete. The American Public Works Association (APWA) utility color code is a standardized system of colors used to mark underground utilities, as illustrated in **Table 2.1**. This code helps prevent damage during excavation by clearly indicating the type of utility present.

Table 2.1 The American Public Works Association utility color code

Color Type	Underground Utilities Line
White	Proposed excavation
Pink	Temporary survey markings
Red	Electric power lines, cables, conduit, and lighting cables
Yellow	Gas, oil, steam, petroleum, or gaseous materials
Orange	Communication, alarm, or signal lines, cables, or conduit
Blue	Potable water
Purple	Reclaimed water, irrigation, and slurry lines
Green	Sewers and drain lines

2.4. Mixture Proportioning

Currently, there is no standard method for CLSM proportioning that matches the concrete proportioning approach. Typically, CLSM proportioning is done through trial and error until a mixture with the right properties for the intended use is created. The flexibility of CLSM enables the use of various materials in its production. This makes it challenging to create a universal mixture proportioning method. Most agencies develop their own CLSM mixture proportions by using locally available materials to achieve the necessary traits, such as flowability, compressive strength, and permeability. Another main goal of CLSM mix design is to lower costs by using materials from local sources. The different application needs and various possible material sources result in a varied CLSM mix design.

Despite the different methods for mix design, ACI suggests three basic methods for CLSM mix design. The first method combines cement materials, fine aggregate, and water, with little to no admixture, to produce CLSM. The second method adds air-entraining admixtures to achieve an air content of 20 to 30% in the mix. The third method aims to create low-density CLSM by combining cementitious materials, water, and foaming agents to reach an air content of 50 to 80%. This approach specifies values for these parameters. These values can be selected based on the desired CLSM properties, allowing the final mix to be created with as few trial mixes as possible. One major drawback of this procedure is that it considers only four constituent materials: fine aggregate, Portland cement, supplementary materials, and water [18].

A performance-based procedure for designing a CLSM mix was proposed by Blanco et al. [52] and Pujadas et al. [56], which consider different project field requirements to optimize the CLSM mix. This defined trial procedure proceeds through three phases: (I) packing optimization, (II) flowability optimization, and (III) strength optimization. Three distinct parameters, i.e., aggregate content (A), binder content (B), and water-to-solid ratio (*w/s*), are optimized to get an optimized CLSM mix. The flowchart of this procedure is depicted in **Figure 2.1**. The first phase enhances the solid system, comprising binder and aggregate, to achieve the highest packing density. The second phase sets an optimized water-to-solid (*w/s*) ratio for the desired workability. Finding the *w/s* ratio allows for adjustments in binder content and helps achieve the targeted compressive strength while maintaining the mixture's workability. This method can decrease the number of trial mixes needed for CLSM mix proportioning.

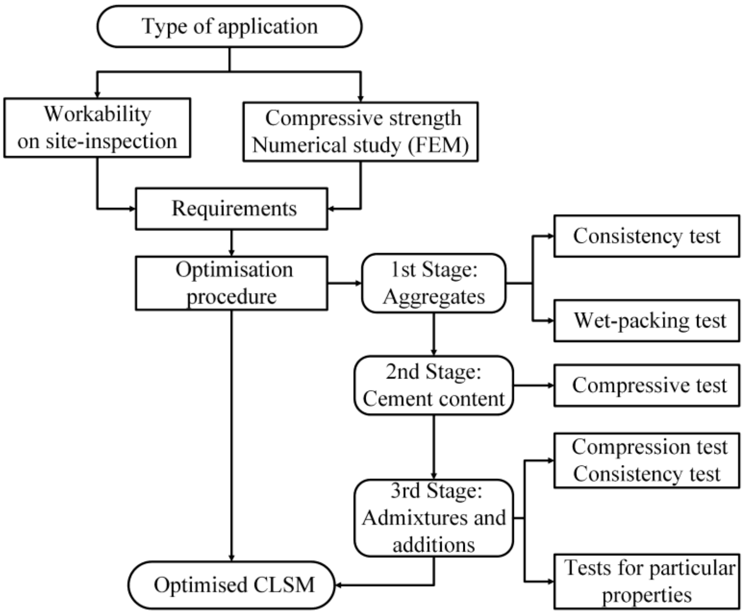


Figure 2.1 General methodology for the design of optimized CLSM

2.5. Properties of CLSM

This section provides information on the properties of CLSM that most significantly affect its performance in key applications, as per Folliard et al. [20]. In buried pipe applications, fresh properties such as flowability, wet density, bleeding, and hardening time are crucial. Hardened properties, including unconfined compressive strength, water permeability, and excavatability, are also important. Hence, this literature review primarily focuses on gathering information on the most critical properties of CLSM, including fresh, hardened, and durability-related aspects. These properties are briefly described in the following sections.

2.5.1. Fresh CLSM Properties

a) Flowability

The key feature of flowability in CLSM enables it to self-level and fill voids effectively. To measure its properties, engineers use slump and flow tests. These are the standard methods for conventional concrete. The level of flowability needed for each application varies; more flowability is needed for areas with restricted access and complex shapes. One of the best advantages of CLSM compared to other backfill materials is that it retains its original properties when fresh. Because it flows easily, CLSM can be placed more quickly and efficiently than other backfill materials, and it does not require compaction or vibration. This reduces the amount of work that needs to be done, makes construction safer, and accelerates the process. The flowability of CLSM mixtures can be affected by the CLSM constituents, aggregate gradation and shape, air content, water content, binder type, and quantity. To achieve the desired flowability for a specific application, trial mixtures should be performed.

b) Bleeding

Stability indicates that the CLSM can resist segregation and bleeding. Segregation occurs when larger particles separate from finer ones, while bleeding refers to water moving upward. Maintaining a stable CLSM mix is essential for ensuring uniform properties and avoiding voids or weak spot areas. Similar to segregation experienced with some high-slump concrete mixtures, high water content requirements for high-flowability CLSM mixtures may cause segregation, mainly if flowability is primarily produced by the addition of water [18]. To achieve a highly flowable CLSM that resists segregation, the mixture must contain sufficient fines to ensure good cohesiveness.

c) Hardening time

The time it takes for the CLSM mixture to transition from a plastic state to a solid state, with sufficient strength to support a person's weight, is referred to as the hardening time, according to ACI 229R-13 [18]. The amount and speed of bleed water, along with the type and amount of cementitious material in the CLSM, are essential factors that affect this hardening time. Other factors that impact hardening time include the permeability and saturation level of the surrounding soil in contact with the CLSM, the fluidity of the CLSM, the mixture proportions, the temperature, humidity, and the depth of fill. Smith reported that CLSM mixtures can harden in as little as one hour but usually take three to five hours under normal conditions. Smith [54] reported that the hardening time of CLSM mixtures can be as short as one hour. However, it usually takes three to five hours under normal conditions.

d) Wet density

The wet density of fresh CLSM influences its placement characteristics and the pressure exerted on surrounding structures. The wet density can be adjusted by varying the proportions of aggregates and other components. The wet density of conventional CLSM in place ranges from 1840 to 2320 kg/m^3, which is greater than that of most compacted granular materials. The dry density of CLSM can be expected to be lower than its wet density due to water loss [18].

2.5.2. Hardened CLSM Properties

a) Unconfined compressive strength

The UCS is an essential measure of load-carrying capacity. It is a key property of CLSM that helps in determining its mixtures. Generally, CLSM with a compressive strength between 0.3 and 0.7 MPa is considered to have a bearing capacity comparable to that of well-compacted soil. The compressive strength of CLSM likely stems from two primary factors: particle friction and bonding strength resulting from hydration. Particle friction increases as bleeding occurs, reducing moisture content. Meanwhile, bond strength from hydration develops even when the CLSM is fresh and becomes more significant after bleeding subsides.

b) Water permeability of CLSM

Permeability indicates how well the CLSM can transmit fluids. Lower permeability is preferred in situations where water infiltration or leakage needs to be minimized. For certain applications, the permeability of CLSM becomes crucial; for example, detecting gas leaks in pipelines buried in CLSM mixtures has proven challenging. Typically, CLSM mixtures have permeability values between 10^{-4} and 10^{-5} cm/s, but higher strength and fine-rich mixtures can reach permeabilities as low as 10^{-7} cm/s [18].

c) Excavatability of CLSM

Excavatability means how easily we can remove hardened CLSM if needed. In pipe backfilling applications, the limited long-term strength gain of CLSM mixtures is a significant consideration. It allows for easy re-excavation in the event of a future pipe failure. Excavatability of CLSM can be influenced by several factors, including the composition of the mixture, the type and quantity of cementitious materials, their strength-gaining characteristics, the nature of the soil in contact with the CLSM mixture and its ability to drain water, as well as the excavation method suitable for the application. According to ACI guidelines, excavatability of CLSM can be assessed using three indicators: 28-day compressive strength, long-term strength (measured at 90 to 180 days), and the Removability Modulus (RE) [18].

The specifications for the removable type of CLSM typically limit both the minimum and maximum 28-day compressive strengths, thereby increasing the time required for completion of the approval process. Maximum UCS criteria are provided to ensure excavatability for applications where future removal of the CLSM is desirable, as the first criterion. Relating the ability to excavate CLSM to a measured compressive strength is an arbitrary guide to the engineer. CLSM with a UCS of 0.3 to 0.7 MPa is easily excavated manually using conventional digging equipment. According to the PWRI *Technical Manual for Fluidized Soils* in Japan, a UCS of 200-600 kN/m² is suitable for buried pipe backfilling, while backhoe excavatability requires a 28-day strength range of 500-1000 kN/m. The UCS limit of 28 days is 200-1000 kN/m² targeted for re-excavability in backfilling buried pipes [26].

Because CLSM typically continues to gain strength beyond the conventional 28-day testing period, it is suggested, especially for CLSM with high cementitious content, that long-term (90 to 180 days) strength tests be conducted to estimate the potential for excavatability. In addition to limiting the cementitious content, entrained air can be used to maintain low compressive strength. ACI 229R-13 suggests that CLSM with a long compressive strength of 0.7 MPa or less can be excavated manually and that CLSM with compressive strengths between 0.7 MPa and 2.1 MPa requires heavy equipment, such as backhoes, for excavation [18].

Engineers in Hamilton County, Cincinnati, Ohio, utilized RE to evaluate the excavatability of the CLSM mixtures specified in their CLSM specifications for backfill applications. RE is governed by both the compressive strength and the mass density of CLSM. According to this concept, CLSM mixtures with RE ≤ 1 are deemed removable, while those with RE > 1 are not easily removable [55].

2.5.3. Durability and Environmental Issues Related to CLSM

a) Hexavalent Chromium leaching test

CLSM has proven to be especially well-suited for the consumption of various waste and by-product materials. Therefore, there has been some concern about the potential for leaching heavy metal constituents in by-product materials from CLSM and their impact on the environment. Hexavalent chromium Cr(VI) is found in concrete as chromate, which is produced by the oxidation of trivalent chromium Cr(III) during the manufacturing of Ordinary Portland cement (OPC) clinker [56, 57]. One of the environmental concerns associated with RC recycling is the potential leaching and dissemination of Cr(VI) [58]. It is crucial to mitigate the adverse environmental impacts to enhance the reuse of RC waste.

Horiguchi et al. [40], conducted leaching tests on CLSM using OPC and blast-furnace slag (BFS) cement type B, finding chromium levels of 0.13 mg/L and 0.02 mg/L, respectively. This suggests that BFS cement type B, with insoluble incinerated sewage sludge ash, can control Cr(VI) leaching below the soil quality standard of 0.05 mg/L. Funayama et al. [49] also investigated Cr(VI) detection in laboratory-mixed and truck-mixed fluidized soil, detecting Cr(VI) levels of 0.05 mg/L in both cases. While these levels met standards, they were still notable compared to typical levels. The use of BFS cement type B with IWA fine aggregate can further reduce the detected Cr(VI) levels.

Table 2.2 presents the designated hazardous heavy metal limits according to the environmental quality standards for soil, as per the Ministry of the Environment, Government of Japan.

Table 2.2 Environmental quality standards for soil

Designated hazardous substances	
Heavy metal elements	Limits of heavy metals (mg/L)
Cadmium	≤0.01
Hexavalent Chromium	≤0.05
Mercury	≤0.0005
Selenium	≤0.01
Lead	≤0.01
Arsenic	≤0.01
Fluorine	≤0.8
Boron	≤1

b) Wetting and drying cycles

The response of CLSM to wetting and drying cycles is essential for its long-term durability. Generally, CLSM mixtures are not designed to withstand freezing and thawing, abrasive or erosive forces, or aggressive chemicals [18]. The majority of previous studies on CLSM employed methods derived from the ASTM D559 standard, which recommends 5 hours of water immersion at room temperature, followed by 42 hours in an oven at 71°C, to investigate wetting-drying effects [44, 47, 59]. These tests are used to evaluate the durability of soil–cement mixtures compacted at the optimum moisture content.

Achtemichuk et al. [47] evaluated the durability of CLSM through 12 freeze-thaw and wet-dry cycles as per ASTM D560 and ASTM D559, respectively. Results indicated that CLSM with 10% fine/coarse RCA and 20% slag had high resistance to degradation, as the mass loss values were way below the 14% limit. Generally, resistance to freeze-thaw and wet-dry cycles correlated positively with compressive strength. Huang et al. [59] also examined specimens that underwent 0–6 cycles of drying–wetting or freeze–thaw action. After six drying–wetting cycles, the specimens experienced a 27– 51% reduction in strength compared to those with no drying–wetting. The study also found that variations in mass loss followed a similar pattern to the strength data.

2.6. Particle Size Distribution of IWA Fine Aggregate

Osaka-Hyogo RMC Industrial established a working group to study the effective utilization of recycled aggregates and published a manual on the subject. According to the *Manual for Effective Utilization of Recovered Aggregates Fine Aggregate System* [60] and *Complete Recycling of Return Concrete "IWA System"* [61] IWA fine aggregates manufactured using the IWA system have some variations in the physical properties of fine aggregates, such as acceptable particle content, unit volume mass, actual rate, dry density, water absorption rate, coarse grain rate, and surface dry density, depending on the nominal strength of the return concrete, which is the source of the IWA fine aggregate, and the storage conditions after the IWA fine aggregate is manufactured. Since the nominal strength of concrete varies depending on the formulation, type of material, and production area, it is not practical to maintain it at a constant level. The properties of the IWA fine aggregates-based concrete showed greater variability and changes in properties than those of ordinary concrete [62].

Funayama et al. [49] investigated the effects of the gradation zone of IWA fine aggregate in fluidized soil. The freshness properties of these features were investigated, and the gradation zone that lies outside the range between No. ④ and No. ⑤ showed such features, indicating the state of viscosity and material separation. Since it was determined that they were within the allowable range, the fresh properties were described as before separation, and they were found

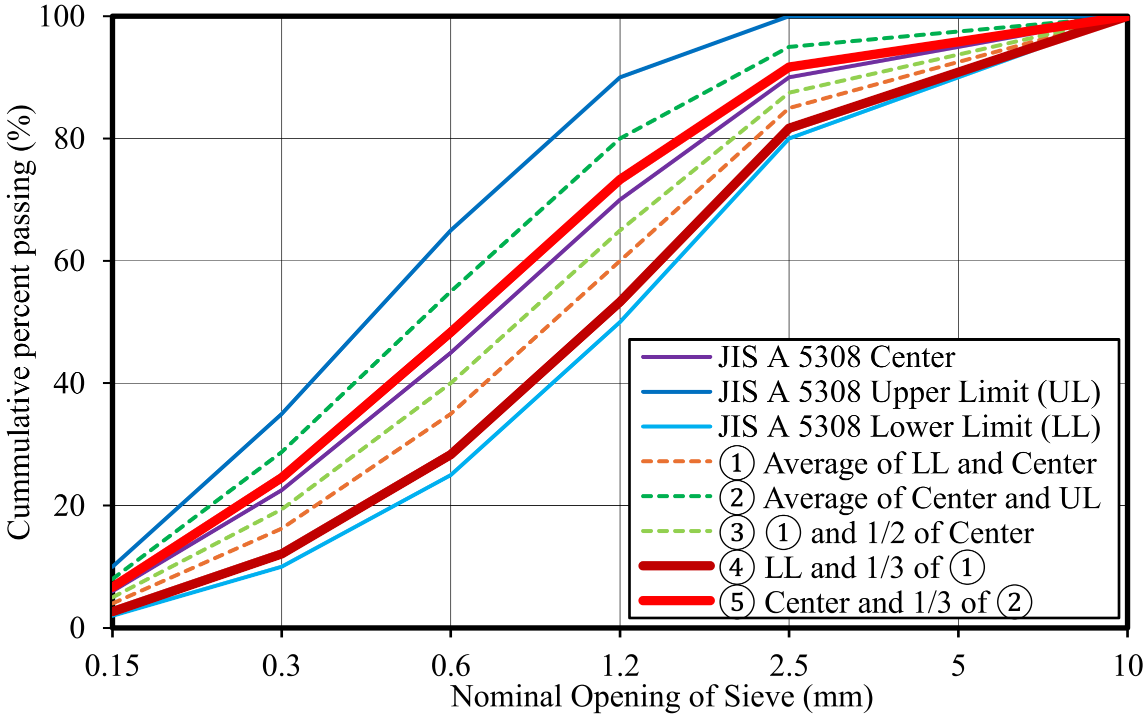


Figure 2.2 IWA fine aggregate gradation zone in fluidized soil

to be viscous. As depicted in **Figure 2.2**, the recommended range of gradation zones to achieve better performance for fresh properties was between the gradation zones of No. ④ and No. ⑤.

2.7. CLSM Application in Utility Trench Backfilling

The broad applicability of any material drives researchers to investigate its behavior and properties to maximize its effectiveness in use. CLSM, primarily utilized as an alternative to compacted soil for backfill or structural fill, later finds applications in specific areas such as pavement bases, conduit bedding, void filling, insulation and isolation fill, thermal insulation conductivity fills, nuclear facilities, corrosion control, and erosion control [19]. This section of the study outlines the applications of CLSM in utility trench backfilling around buried pipes and conduit bedding, providing a comprehensive understanding of its significance from an engineering perspective.

Ling et al. [63] reviewed the global application of CLSM for trench backfilling, identifying 115 relevant articles in the English literature from 1990 to 2017. The overview includes specifications, materials used across countries, and impacts on trench backfilling properties.

Figure 2.3 presents the number of articles by country and year. Notably, approximately one-third of the studies originated from the USA, with an average of 5 articles published globally per year over the last 25 years.

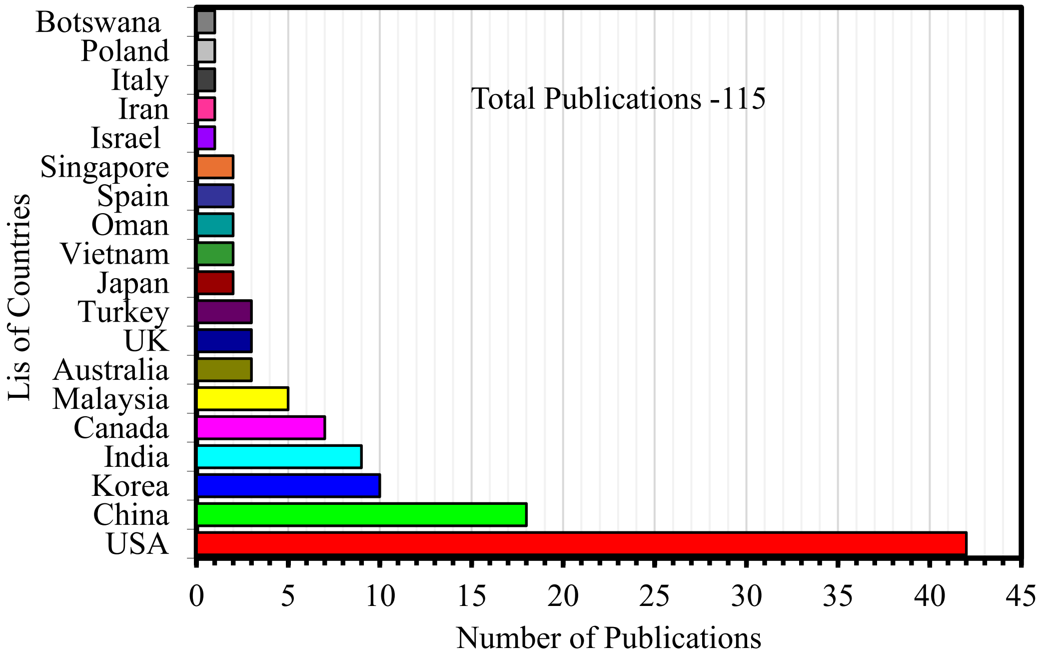


Figure 2.3 Country-wise analysis of articles published related to CLSM

2.7.1. Backfill Around Buried Pipes

CLSM is designed to be flowable, making it easy to place as backfill in trenches, holes, or other cavities. It requires no compaction; therefore, the trench width or excavation size can be reduced. CLSM performs very well as trench backfill when properly mixed. CLSM provides a backfill that does not settle significantly, reduces loading on pipes, is not labor-intensive, allows for quick completion of trench backfill, and develops sufficient strength to support regular traffic within a few hours after placement [63, 64].

Kaneshiro et al. [65] investigated the use of CLSM in pipeline trench backfilling. They focused on particle size distribution, water-to-solid ratio, and binder-to-aggregate ratio as performance parameters, evaluating their effects on the physical and mechanical properties of CLSMs. The optimal mixture ratio was tested in a field experiment, showing the feasibility of the proposed CLSM for trench backfilling.

Ling et al. [63] reviewed 115 literature articles related to trench backfilling, finding that the materials used for CLSM production varied from case to case, significantly impacting both the performance of CLSM and its application in the field. The study also demonstrated that using high-volume by-products and waste effectively controls the low strength requirement of CLSM and minimizes environmental disposal concerns.

Blanco et al. [52] proposed a preliminary methodology for designing optimized CLSM, combining finite element method (FEM) numerical simulations and experimental procedures for backfilling narrow trenches. The authors revealed that a three-stage optimization procedure is included in the methodology, which involves optimizing aggregates, cement content, and admixtures and additions employed.

Liu et al. [66] conducted numerical simulations on buried pipe backfilling, considering three scenarios: loose backfill around the pipe, dense backfill, and CLSM backfill. The findings revealed a significant reduction in pressure on both the top and sides of buried pipes when CLSM was utilized for backfilling purposes.

Figure 2.4 illustrates the trench cross-section details, emphasizing the backfilling of underground utility pipes and bedding in accordance with ASTM D2321.

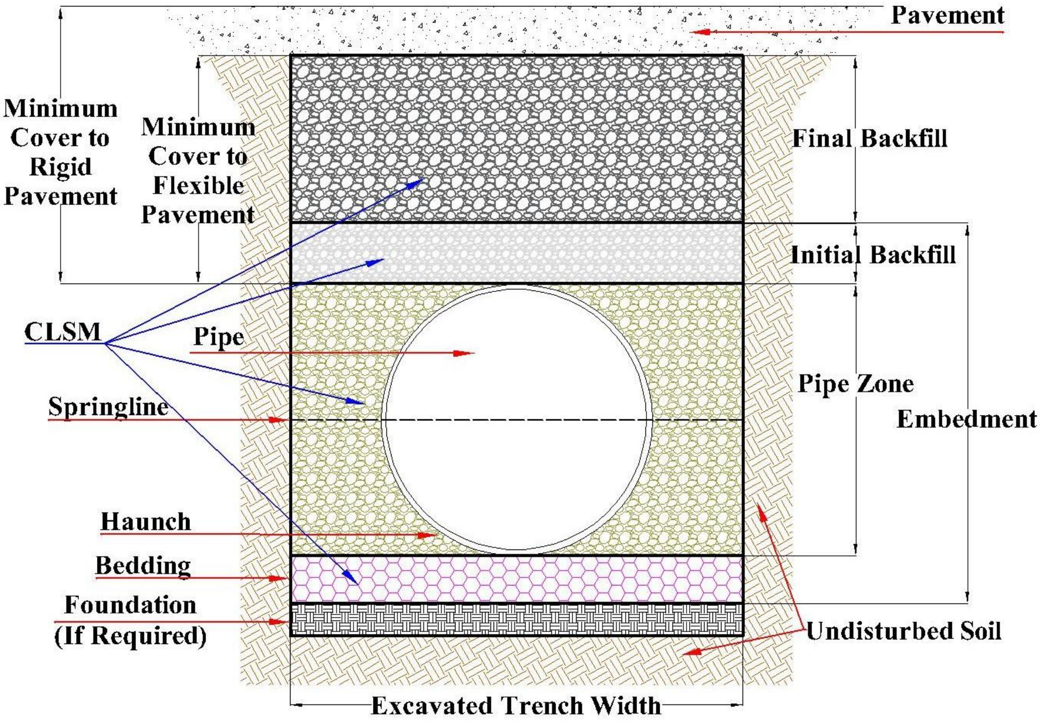


Figure 2.4 Underground utilities trench cross-section

2.7.2. Conduit Bedding

The bedding material is positioned at the base of the trench, located between the foundation and the underside of the pipe. This bedding offers uniform longitudinal support, efficiently distributing the load from the base of the pipe. The thickness of the bedding should be no less than 10 cm for pipes with diameters ranging from 10 cm to 91 cm, and a minimum of 15 cm for pipes with diameters between 106 cm and 150 cm. [67, 68].

The flowability of CLSM makes it an excellent choice for bedding material, as it flows and fills the voids beneath conduits, providing a uniform bedding surface. It is utilized as bedding for pipes, electrical, and telephone conduits [18]. The U.S. Bureau of Reclamation first reported using CLSM in this capacity in 1964. It was noted that employing soil-cement slurry for bedding reduced costs by 40% and increased the efficiency of pipe installation per shift [69]. Another advantage of CLSM as conduit bedding is its erosion resistance, which prevents water from accumulating between the conduit and the bedding [70].

Boschert and Butler [71] investigated the use of CLSM as pipe bedding and calculated a predicted load using the modified Marston equation. The results show a load transfer mechanism in which the load on the pipe can be decreased by the ratio of the outside diameter of the pipe to the width of the trench at the top of the pipe.

2.8. Standard Guideline and Specifications of CLSM

2.8.1. American Concrete Institute (ACI) Guideline

In 1984, to increase awareness and disseminate more information regarding CDF, Mr. Brewer approached ACI and suggested forming a committee for low-strength materials. That year, the ACI Committee 229 on CLSM was created, and Mr. Brewer served as the chairman for six years. The term CLSM was chosen over CDF because it is more general, covering a wider range of filling materials. The pioneering members of ACI 229 determined that the definition of CLSM was to be those materials with a 28-day compressive strength of less than 8.3 MPa, regardless of the materials used to produce the mixture.

Ten years after the formation of ACI Committee 229, under the chairmanship of Wayne Adaska, the report on CLSM was completed. It appeared in the July 1994 edition of Concrete International. The distribution of this document increased awareness and understanding of CLSM. The report, which serves as a guide to CLSM, begins with an introduction that includes a definition, other relevant terms, and a table outlining the advantages of using CLSM.

The ACI 229 Report, in its discussion on quality control, acknowledges a lack of test methods specifically for CLSM. Historically, testing on the CLSM was minimal. If anything was needed, CLSM was treated as a "concrete-like" material with similar testing specified. As the use of CLSM increased, compressive strengths were perceived to be important; therefore, in keeping with the concrete mentality, 28-day strengths were specified.

The revised report ACI-229R-13 document is not only the primary guideline used in the USA but has also been widely referenced by many countries. [63]. It provides valuable advice to purchasers of ready-mixed and site-mixed CLSM on how CLSM should be specified in terms of specific ASTM standards. The principal applications of CLSM include trench backfilling, structural fills, pavement bases, void filling, and conduit bedding [4].

Ling et al. [63] summarizes the criteria, requirements, and essential properties that must be achieved for each distinct application of CLSM, as depicted in **Table 2.3**.

Table 2.3 The criteria requirements for different CLSM applications

CLSM application	Criteria to be fulfilled
General backfilling (Void fillings, filling abandoned underground structures, etc.)	High degree of flowability (> 200 mm spread)
	Durability properties
	Setting time and early strength is not critically essential.
	28-day UCS should be 0.5MPa
Excavatable backfilling (Underground pipelines-water, sewer, and storm Drainage pipelines, roadway trench, conduit bedding, etc.)	High degree of flowability
	Self-compacting and self-leveling
	Less subsidence and quick setting time
	Durability properties
	Easy for re-excavation–Manually or mechanically
	28-day UCS 2.1MPa
Structural backfilling (Bridge approach, foundation support, retaining walls, etc.	Good flowability (at least 200 mm spread)
	Self-compacting and permanent fill
	Uniformity, stability, and durability properties
	28-day UCS should be controlled within 0.7–8.3MPa
Pavement backfilling (Sub-bases, subgrades of flexible pavement)	Good flowability
	Self-compacting and self-leveling
	Early strength and short hardening time are essential
	Wearing and freeze-thaw resistance
	Durability properties
	28-day UCS should be controlled within 2.8–8.3MPa
Thermal backfilling (Underground power cables)	High degree of flowability
	Self-compacting and self-leveling
	Early strength and durability properties
	High density and low porosity
	High thermal conductivity
	28-day UCS 2MPa
Anticorrosion backfilling (Underground metal pipelines)	High degree of flowability
	Self-compacting and self-leveling
	Early strength, uniformity, and durability properties
	High electrical resistivity
	28-day UCS 2MPa

2.8.2. Technical Manual of Fluidized Soil in Japan

In Japan, liquefied soil stabilization methods have been widely adopted in various construction projects, enabling the effective reuse of geotechnical materials generated during construction. The "*Technical Manual for Fluidized Soils*" is a crucial standard for the stabilization and reuse of liquefied soil in geotechnical applications [26]. This manual is widely used by all parties concerned and will contribute to promoting the recycling of construction-generated soil. Fluidized soil is kneaded by adding mud water (or ordinary water) containing a large amount of water and a solidifying material to the soil. The fluidization treatment method uses various types of soil (including construction sludge) generated from the construction site as the primary material. The fluidization treatment method involves adding soil, mud, and water containing fine particles to the sand, producing mud-like soil with a particle size configuration and water content ratio that meets the required quality [72].

The development of utilization technology for fluidized treated soil aims to promote the recycling of generated soil. It is desirable to manufacture and use high-density treated soil, utilizing as much raw soil as possible. To achieve this, it is necessary to maximize the utilization rate of generated soil while ensuring the fluidity required for construction. Fluidized treated soil, since it has fluidity and self-hardening and does not require compaction, is particularly effective when used for backfilling and filling under challenging places of compaction. The "*Technical Manual for Fluidized Soils*", a key Japanese technical manual, incorporates advancements in fluidized soil technology, and its principles can be applied to CLSM due to the similarities between the two materials. This research includes both the Japanese manual and ACI guidelines to provide a comprehensive approach to the utilization of CLSM.

According to the "*Technical Manual for Fluidized Soils*", manufactured fluidized soils are required to achieve four desirable quality control parameters: uniaxial compressive strength, wet density, bleeding rate, and flow value. The fluidized soil has a wide range of applications due to its unique characteristics and properties. The principal applications of fluidized soil include backfilling underground structures, civil structures, underground spaces, small cavities, buried pipes, conduit bedding, around foundations, underwater structures, and invert sections of shield tunnels. **Table 2.4** summarizes the targeted criteria requirements and the essential properties that need to be achieved for each different application of fluidized soil, as outlined in the *Technical Manual for Using Fluidized Soils*.

Table 2.4 Target values for application to the liquefied stabilized soil

Application Target	Quality Items	Standard Value
Backfilling underground structures	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.5 g/cm^3 or more
	UCS (kN/m^2)	300 kN/m^2 or more (However, if the wet density is 1.6 g/cm^3 or more, it is 100 kN /m^2 or more)
Backfilling civil structures	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.6 g/cm^3
	UCS (kN/m^2)	100 kN/m^2 or more
Backfilling underground spaces	Flowability (mm)	200 mm or more
	Bleeding rate (%)	Less than 3%
	Wet density (g/cm^3)	1.4 g/cm^3 or more
	UCS (kN/m^2)	300 kN/m^2 or more (However, if the wet density is 1.6 g/cm^3 or more, it is 100 kN /m^2 or more)
Backfilling small cavities	Flowability (mm)	200 mm or more
	Bleeding rate (%)	Less than 3%
	Wet density (g/cm^3)	1.4 g/cm^3 or more
	UCS (kN/m^2)	300 kN/m^2 or more (However, if external force does not act, it is 100 kN /m^2 or more)
Backfilling buried pipes	Maximum particle Size (mm)	13 mm or less
	Flowability (mm)	140 mm or more
	Bleeding rate (%)	Less than 3%
	Wet density (g/cm^3)	1.4 g/cm^3 or more
	UCS (kN/m^2)	28-day UCS: 200-600 kN/m^2. Hardening time [at least 130 kN/m^2 under roads and 50 kN/m^2 under sidewalks when open to traffic]

Receiving and protecting buried pipes	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.4 g/cm^3 or more
	UCS (kN/m^2)	300 kN/m^2 or more (However, if the wet density is 1.6 g/cm^3 or more, it is 100 kN /m^2 or more)
Backfilling around foundations	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.6 g/cm^3 or more
	UCS (kN/m^2)	100 kN/m^2 or more
Backfilling large diameter buried pipes	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.6 g/cm^3 or more
	UCS (kN/m^2)	200 kN/m^2 or more
Backfilling building foundations	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.8 g/cm^3 or more
	UCS (kN/m^2)	More than 3 times of required bearing capacity
Backfilling underwater structures	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.4 g/cm^3 or more
	UCS (kN/m^2)	400 kN/m^2 or more (However, if the water-permeable treatment is done wet density, it is 200 kN /m^2 or more)
Backfilling invert sections of shield tunnels	Flowability (mm)	110 mm or more
	Bleeding rate (%)	Less than 1%
	Wet density (g/cm^3)	1.6 g/cm^3 or more
	UCS (kN/m^2)	6000 kN/m^2 or more

2.9. Testing Standard for CLSM

The quality control program for CLSM depends on experience, application, materials, and desired quality. The fresh and hardened properties of CLSM can be evaluated to assess the consistency and performance of the mixture. Standard testing methods and acceptance criteria for concrete typically do not apply in this case. Testing standards for CLSM are crucial for ensuring a consistent evaluation of its properties, which in turn facilitates quality control and performance assessment. According to Folliard et al. [20], there are recommended test methods (whether existing, modified, or new) that can measure a comprehensive range of CLSM properties.

Currently, there are only five ASTM standard test methods available for evaluating CLSM mixtures. Furthermore, it may be necessary to modify some of the existing ASTM test methods of concrete to more accurately gauge parameters that can enhance the assessment of the properties and characteristics of CLSM. Additionally, the tests currently employed to evaluate CLSM exhibit significant variability across different laboratories or agencies. **Table 2.5** presents the five ASTM standard test methods for the evaluation of CLSM mixtures developed by the ACI Committee on Soil and Rock.

Table 2.5 Test methods for the determination of CLSM mixtures as per ACI guidelines

Categories	**Property**	**Test Methods**	**Description**
Fresh CLSM Test Methods	Sampling	ASTM D 5971	Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material
	Flowability	ASTM D 6103	Standard Test Method for Flow Consistency of Controlled Low-Strength Material
	Unit weight and air content	ASTM D 6023	Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material
	Hardening time	ASTM D 6024	Standard Test Method for Ball Drop on Controlled Low-Strength Material to Determine the Suitability of Load Application
Hardened CLSM Test Methods	Unconfined compressive strength	ASTM D 4832	Standard Test Method for Preparation and Testing of Controlled Low-Strength Material Test Cylinders

In Japan, liquefied soil stabilization methods have been widely adopted in various construction projects, enabling the effective geotechnical reuse of construction-generated soil. The "*Technical Manual for Fluidized Soils*", a key Japanese technical manual, incorporates advancements in fluidized soil technology, and its principles can be applied to CLSM due to the similarities between the two materials.

The *Technical Manual of Fluidized Soils* recommends using JIS testing methods, which were not initially developed for fluidized soils but can be applied to them. Although this method is intended for fluidized soil, it serves as an equivalent means of testing that aligns with the standards for CLSM, thereby facilitating consistent evaluations of its properties and helping in quality control. Both ASTM and JIS provide relevant testing standards. ASTM standards are more widely adopted in the United States, while JIS standards are commonly used in Japan.

Table 2.6 presents the standard test methods for evaluating fluidized soil, which can be applied to CLSM mixtures.

Table 2.6 Test methods for the determination of fluidized soil mixtures

Categories	Properties	Test Methods	Description
Fresh CLSM Test Methods	Flowability	JHS A 313-1992	Test Methods for Air Mortar and Air Milk
	Bleeding rate	JSCE F 522	Test Method for Bleeding Rate and Expansion Rate of Injection Mortar of Prepacked Concrete (Polyethylene Bag Method)
	Wet density	Constant Volume Method	Measure the mass of the CLSM sample filled in a container of known volume and divide it by the volume of the container
	Air content	JIS A 1128	Method of test for air content of fresh concrete by the pressure method
	Hardening time	JIS A 1147	Method of test for the time of setting of concrete mixtures by penetration resistance
Hardened CLSM Test Methods	Unconfined compressive strength	JIS A 1216	Unconfined Compression Test Method for Soil

2.10. Advantages of Controlled Low-Strength Materials

There are several inherent advantages to using CLSM over compacted fill in various applications. The advantages of CLSM are well documented in literature. In 1991, a list of 15 main advantages of CLSM was published [54]. The list was later adopted by the ACI 229 committee and included in their report on CLSM. **Table 2.7** presents the advantages of using CLSM in place of granular compacted material as per ACI 229R-13.

Table 2.7 Cited Advantages of CLSM (ACI 299R-13)

Advantages	Description
Readily available	Using locally available materials, RMC suppliers can produce CLSM to meet most project specifications.
Easy to deliver	Truck mixers can deliver specified quantities of CLSM to job site whenever material is needed.
Easy to place	Depending on type and location of void to be filled, CLSM can be placed by chute, conveyor, pump, or bucket. Because CLSM is self-leveling, it needs little or no spreading or compacting. This speeds construction and reduces labor requirements.
Versatile	CLSM mixtures can be adjusted to meet specific fill requirements. Mixes can be adjusted to improve flowability. More cement or fly ash can be added to increase strength. Admixtures can be added to adjust setting times and other performance characteristics. Adding foaming agents to CLSM produces lightweight, insulating fill.
Strong and durable	Load-carrying capacities of CLSM are typically higher than those of compacted soil or granular fill. CLSM is also less permeable, thus more resistant to erosion. For use as permanent structural fill, CLSM can be designed to achieve 28-day compressive strength as high as 8.3 MPa.
Allows fast return to traffic	Because many CLSMs can be placed quickly and support traffic loads within several hours, downtime for pavement repairs is minimal.
Will not settle	CLSM does not form voids during placement and does not typically settle or rut under loading. This advantage is especially significant if the backfill is covered by a pavement patch. Soil or granular fill, if not consolidated properly, may settle after a pavement patch is placed, forming cracks or dips in the road.

Reduces excavation costs	CLSM allows for narrower trenches because it eliminates the need to widen trenches to accommodate compaction equipment.
Improves worker safety	Workers can place CLSM in a trench without entering the trench, reducing their exposure to possible cave-ins.
Allows all-weather construction	CLSM will typically displace any standing water left in a trench from rain or melting snow, reducing the need for dewatering pumps. To place CLSM in cold weather, materials can be heated using the same methods for heating RMC.
Can be excavated	CLSM having compressive strengths of 0.3 to 0.7 MPa is easily excavated with conventional digging equipment yet is strong enough for most backfilling needs.
Requires less inspection	During placement, soil backfill must be tested after each lift for sufficient compaction. CLSM self-compacts consistently and does not need this extensive field testing.
Reduces equipment needs	Unlike soil or granular backfill, CLSM can be placed without loaders, rollers, or tampers.
Requires no storage	Because ready-mixed concrete trucks deliver CLSM to job site in quantities needed, storing fill materials on site is unnecessary. Also, there is no leftover fill to haul away.
Makes use of coal combustion product	Fly ash is by-product produced by power plants that burn coal to generate electricity. CLSM containing fly ash benefits environment by making use of this industrial product material.

2.11. Challenges and Limitations of Controlled Low-Strength Materials

Although CLSM offers numerous advantages over compacted fill, its use has gained increased acceptance in recent years; however, it also faces challenges that hinder its widespread adoption in the industry, despite its potential. One reason is that CLSM is somewhat of a hybrid material; it is a cementitious material that behaves more like a compacted fill. As such, much of the information and discussions on its uses and benefits have fallen between the cracks of concrete materials and geotechnical engineering.

The lack of standardized testing requirements is another impediment to the use of CLSM. Many procedures for testing CLSM follow the same ASTM standards used to test concrete. Engineers and testing laboratories often rely on the same ASTM standards used for concrete testing to evaluate CLSM. A standard suite of testing procedures for CLSM needs to be developed that measures all key characteristics of CLSM, which have significant effects on its performance in its specific application.

Many states have developed specifications (in some cases, provisional) that govern the use of CLSM. However, these specifications vary from state to state, and moreover, a range of different test methods are currently used to define the same intended properties. This lack of conformity, both in specifications and testing methods, has also hindered the proliferation of CLSM applications.

There are also technical challenges that have hindered the widespread use of CLSM. For instance, it is often observed in the field that excessive long-term strength gain may make it difficult to excavate CLSM at later ages. This strength gain can be a significant issue, resulting in increased costs and labor. Other technical issues deserving attention are the compatibility of CLSM with different types of utilities and pipes, the potential leaching of constituent materials, and the durability of CLSM subjected to freezing and thawing cycles.

Another challenge associated with CLSM is the lack of construction standards and procedures compared to conventional backfill materials. Although many cities' public works departments, utility companies, and state transportation departments have been using CLSM for backfilling since the 1970s, no universal standards have been established for its application. The NRMCA and many state RMC associations have published recommended mix designs and placement procedures for CLSM.

The ACI 229R-13 states that CLSM could displace standing water left in a trench from rain or melting snow and deems dewatering pumps unnecessary. However, contractors have reported that even a small amount of additional water in the trench can cause segregation of some CLSM mixtures [28]. The flotation of pipes due to the fluid nature of CLSM is also a construction concern that may require additional pipe-fixing measures or placement height limits for CLSM applications.

CHAPTER 3: EXPERIMENTAL METHODOLOGY

3.1. Introduction

This chapter presents the experimental procedures used to examine the fresh properties, hardened properties, and durability of eco-friendly controlled low-strength material (CLSM) that utilizes improved water absorption (IWA) fine aggregate, concrete sludge powder (CSP), and ground granulated blast-furnace slag (GGBFS). The methodology covers the selection and preparation of materials, the optimization of mix design, casting and curing of specimens, testing of both fresh and hardened properties, durability evaluation, and the development of a gradation zone for IWA fine aggregate. Each optimization step is carefully planned to ensure reliable and valid results, contributing to a thorough understanding of the performance of eco-friendly CLSM made from fresh returned concrete (RC) waste materials combined with industrial by-products.

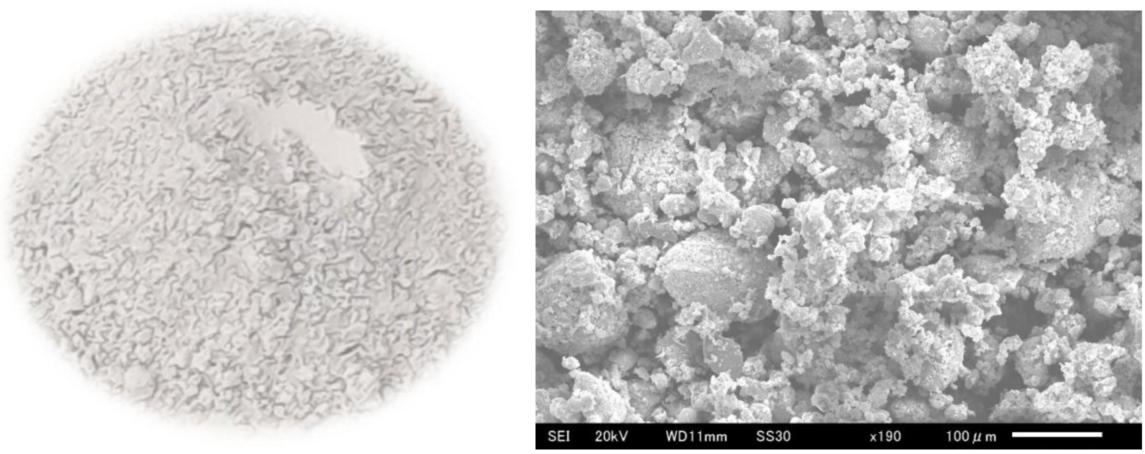
The properties of the materials used in this study, such as GGBFS, IWA fine aggregate, CSP, supernatant water, and super-retardant geoliter 10, are provided in section 3.2. Details of the laboratory testing program and mix proportions are outlined in section 3.3. The preparation of specimens, testing methods, and gradation formulation of IWA fine aggregate in CLSM mixtures are detailed in sections 3.4 and 3.5, respectively.

3.2. Materials Properties

The American Concrete Institute (ACI) 229R-13 specification provides guidelines for selecting CLSM constituent materials, but it does not mandate the strict use of standardized materials [18]. Instead, the material selection process should prioritize factors such as material availability, cost-effectiveness, the specific application, and the desired properties of both the fresh and hardened CLSM mixture. This flexible approach allows for the utilization of a variety of waste materials, including industrial by-products and recycled materials, as long as they meet the necessary requirements for the targeted application [19]. The two primary constituent material categories used in producing the eco-friendly CLSM mixtures in this investigation were: industrial by-products employed as the binder, and fully recycled, fresh RC waste utilized as the fine aggregate, filler, and mixing water.

3.2.1. Ground Granulated Blast Furnace Slag (GGBFS)

In this study, GGBFS, an industrial by-product from pig iron production, is employed as the binder for the eco-friendly CLSM mixtures. The use of GGBFS aligns with sustainable construction practices, as it reduces the environmental impact associated with conventional binder production. GGBFS contributes to minimizing the ecological footprint through resource conservation and lower CO_2 emissions during manufacturing, while also mitigating the leaching of certain heavy metals. The grade of GGBFS material employed in this study is GGBFS 4000, having a density of 2.89 g/cm^3 and a specific surface area of 4370 cm^2/g, conforming to Japanese Industrial Standard (JIS) A 6206. The physical and chemical properties of the GGBFS 4000 are shown in **Table 3.2**. Additionally, an SEM test was conducted to study the shape of GGBFS, as depicted in **Figure 3.1**.



a) GGBFS b) GGBFS SEM test

Figure 3.1 GGBFS Shapes

3.2.2. Improved Water Absorption (IWA) Fine Aggregate

The IWA fine aggregate employed in this investigation, obtained from the Nagaoka RMC in Shizuoka, Japan, was used as the fine aggregate. It has a surface dry density of 2.03 g/cm^3 and a water absorption of 14.2%. As depicted in **Figure 3.2**, the particle-size distribution of this IWA fine aggregate, with all particles passing through a 10 mm nominal sieve size, aligns with JIS A 5308.

The basic physical properties of the IWA fine aggregate are summarized in **Table 3.1**. Additionally, an SEM test was conducted to study the shape of IWA fine aggregate, as depicted in **Figure 3.3**.

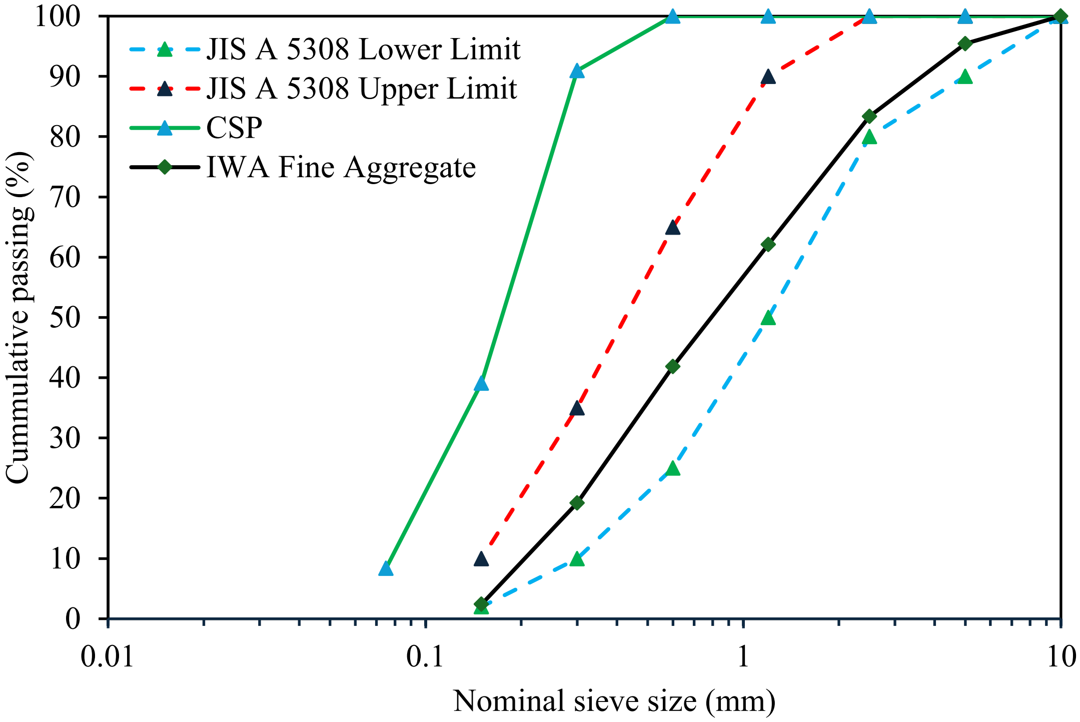


Figure 3.2 Particle size distribution of materials used in this study

Table 3.1 The basic physical properties of the IWA fine aggregate

Materials	Surface dry density (g/cm^3)	Oven-dry density (g/cm^3)	Water absorption (%)	Unit volume mass (kg/l)	Fine particle content (%)	Fineness modulus
IWA fine aggregate	2.03	1.94	14.2	1.24	1.2	2.96

The production of IWA aggregate at Nagaoka RMC involves a series of steps carried out at concrete plants as shown in **Figure 3.4**. In order to accommodate the daily volume of fresh returned concrete, the material was discharged and collected into a designated storage pit, rather than processing it within the truck mixer. At the end of each delivery day, the recovery process was carried out in the pit. The procedure involved adding a superabsorbent polymer after a few minutes of mixing, using an excavator bucket, which transformed the returned concrete into a granular material. An ettringite-forming compound was then added, followed by an additional 2-3 minutes of mixing, curing, and sieving to achieve the desired gradation for use as fine or coarse aggregate. The resulting granular material is then transferred to a drying bay. The granular material is sieved to obtain the desired fine or coarse IWA aggregate, which can then be stockpiled or stored in airtight plastic containers or packaged.

a) IWA fine aggregate b) IWA fine aggregate SEM test

Figure 3.3 IWA fine aggregate shapes

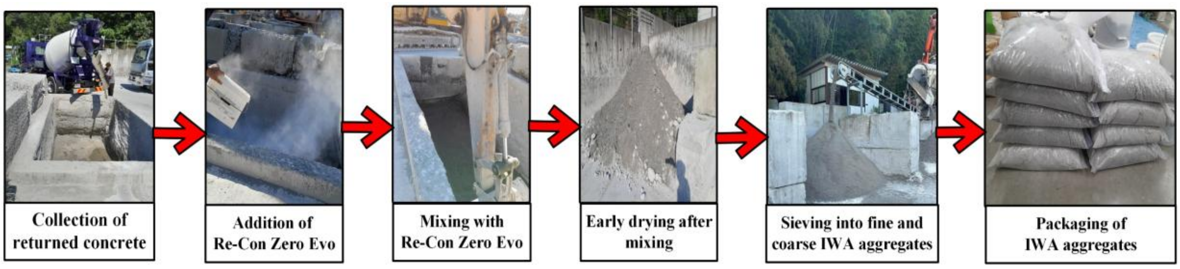


Figure 3.4 Production stages of IWA aggregates

3.2.3. Concrete Sludge Powder (CSP)

The filler material utilized in this study is CSP, a recycled by-product obtained from the Nagaoka RMC and Shiraishi RMC companies in Japan, where it is locally known as *Zankona*. This material serves as a sustainable filler component in the production of CLSM. The CSP is derived from leftover concrete sludge cake that undergoes a systematic processing regimen at the RMC production facility, transforming it from waste into a valuable resource suitable for CLSM applications.

The production process at RMC begins with an extensive drying phase to reduce the initially high moisture content of the raw sludge cake. Following dehydration, the material undergoes mechanical crushing to achieve particle size reduction, with all particles engineered to pass through a 0.60 mm nominal sieve size (**Figure 3.2**). The third stage involves air separation technology to isolate the fine powder from coarser sludge sand particles. It has a density of

1.89 g/cm^3. Additionally, an SEM test was conducted to study the shape of CSP, as depicted in **Figure 3.6**.

Concrete sludge waste generated at concrete plants is collected in sedimentation pits and dewatered to reduce moisture content. The dried sludge cake is then crushed mechanically into a fine powder. The dust collection system is employed to separate the fine CSP particles from the coarser sludge sand. The collected CSP is then packed and stored in unopened bags under cool and dry conditions. The integration of this processed CSP as a filler in CLSM production represents an environmentally responsible approach to construction materials, effectively repurposing a waste stream from concrete production while reducing the demand for virgin materials in CLSM applications. **Figure 3.5** shows the production process at Shiraishi RMC, from concrete collection to CSP packaging.

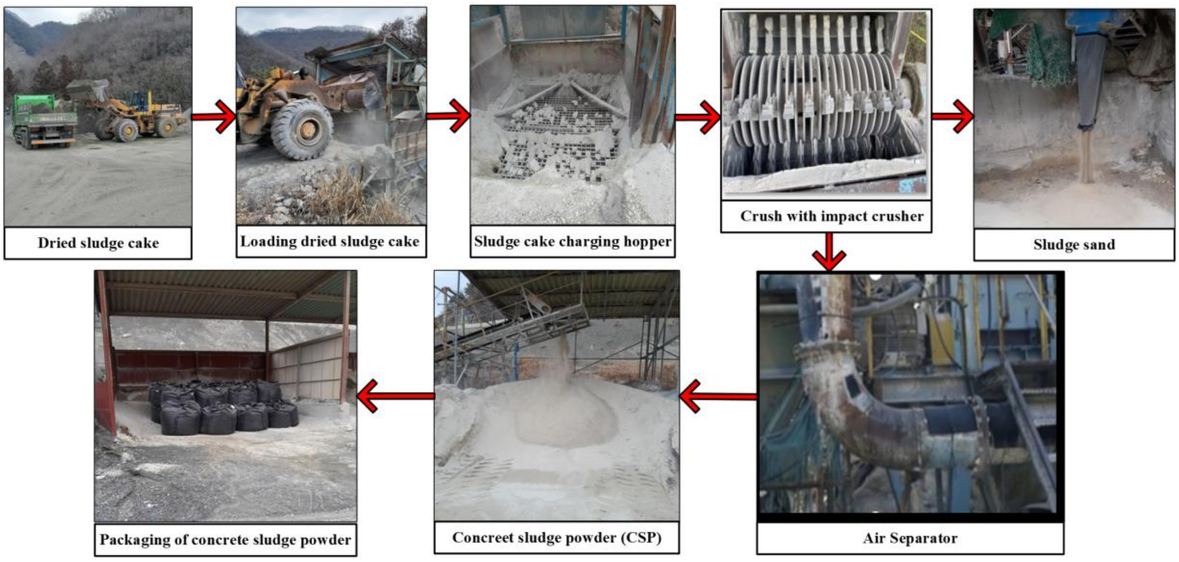


Figure 3.5 Production stages of concrete sludge powder

a) CSP b) CSP SEM test

Figure 3.6 Concrete sludge powder (CSP) shapes

The chemical composition of the materials used is presented in **Table 3.2**. It is observed that CSP and IWA fine aggregate mainly contained Ca and Si, as the cement did [14]. The high CaO content in IWA fine aggregates (67.99 %), CSP (64.52 %), and GGBFS (42.03 %) suggests the presence of calcium-based compounds in these materials. Calcium compounds, such as calcium hydroxide, play a crucial role in the development of strength in cementitious materials. The presence of CaO indicates the potential for the formation of additional calcium-rich compounds during the hydration process, further enhancing the strength characteristics of the CLSM [73]. The chemical composition of GGBFS is essential for its hydraulic activity. GGBFS can be classified based on its basic index, which is determined by its chemical composition. The ratio of calcium to siliceous oxide must be more than one to be effective [74].

The presence of SiO_2 (33.02 %, 18.47 %, 16.61 %) and Al_2O_3 (14.44 %, 3.58 %, 2.89 %) in GGBFS, CSP, and IWA fine aggregate, respectively, indicates the potential for these constituents to contribute to the binding and strength development of CLSM. Both SiO_2 and Al_2O_3 are known to participate in pozzolanic reactions when combined with suitable activators, such as calcium hydroxide, during hydration. These reactions result in the formation of additional cementitious compounds, contributing to the overall strength and durability of the CLSM matrix.

The presence of high Fe_2O_3 content in IWA fine aggregates 9.81%) and CSP 8.73%) suggests the possible presence of iron oxide in the returned concrete sludge. Iron oxide can act as a coloring agent in cementitious materials but does not significantly contribute to strength development. The presence of unhydrated cement particles within the returned fresh concrete provides a source of calcium hydroxide that participates in carbonation reactions, enhancing the long-term performance of the CLSM.

Table 3.2 Chemical composition of materials used in this study

Materials	Chemical Composition (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	MnO	ZnO	K_2O
GGBFS	33.02	14.44	0.79	42.03	5.80	2.00	0.41	-	-	0.65
CSP	16.61	2.89	8.73	67.99	-	1.47	0.74	0.18	0.12	0.88
IWA fine aggregate	18.47	3.58	9.81	64.52	-	2.13	0.84	0.22	0.14	-

3.2.4. Supernatant Water

Supernatant water, recycled from concrete washing wastewater at the Nagaoka RMC in Shizuoka Prefecture, was employed as the mixing water for the CLSM mix. This supernatant water, characterized by a density of 1.0 g/cm^3 and an alkaline pH of 11 due to the presence of a significant amount of calcium hydroxide ($Ca(OH)_2$), serves as a complete replacement for tap water in CLSM production [17].

The application aligns with quality requirements for non-potable water outlined in JIS 5308, depicted in **Table 3.3**, with the high alkalinity potentially influencing the hydration kinetics and setting behavior of cementitious materials in the CLSM mixture [75]. The utilization of supernatant water addresses two critical sustainability concerns: reducing freshwater consumption by recycling process water and eliminating environmental hazards associated with untreated concrete wastewater disposal, as highlighted by [17] and [50]. This approach represents a practical implementation of circular economic principles in concrete production, transforming a waste stream into a valuable resource.

Table 3.3 Quality of non-tap waters standard for supernatant water

Items	Qualities required as per JIS A 5308:2019						
	Amount of suspended solids	Amount of soluble evaporation residues	Chloride ion (Cl−) content	Differences in cement setting time (minutes)		Mortar Compressive strength ratio (%)	
	(g/L)		(mg/L)	Difference in starting time	Difference in finishing time	7 days	28 days
JIS standard value	2 or less	Less than 1	200 or less	within 30	within 60	Over 90	
Supernatant water	-	-	10.6	10	0	100	101

The production of supernatant water at the Nagaoka RMC follows a systematic process that begins with the collection of returned concrete from construction sites. This is followed by washing concrete mixer trucks, which generate wastewater containing cement particles, aggregates, and chemical admixtures. The wastewater then undergoes sedimentation and filtration, where heavier particles settle at the bottom through gravitational forces. Through a gravity-based collection system, water is separated from the heavier concrete residues and temporarily stored in a dedicated sludge water tank. The water undergoes further purification through sand pump filtration to remove remaining fine particles before the clarified supernatant water is collected in a dedicated tank. **Figure 3.7** shows the production process at Nagaoka RMC, from concrete collection to supernatant water collection tanks.

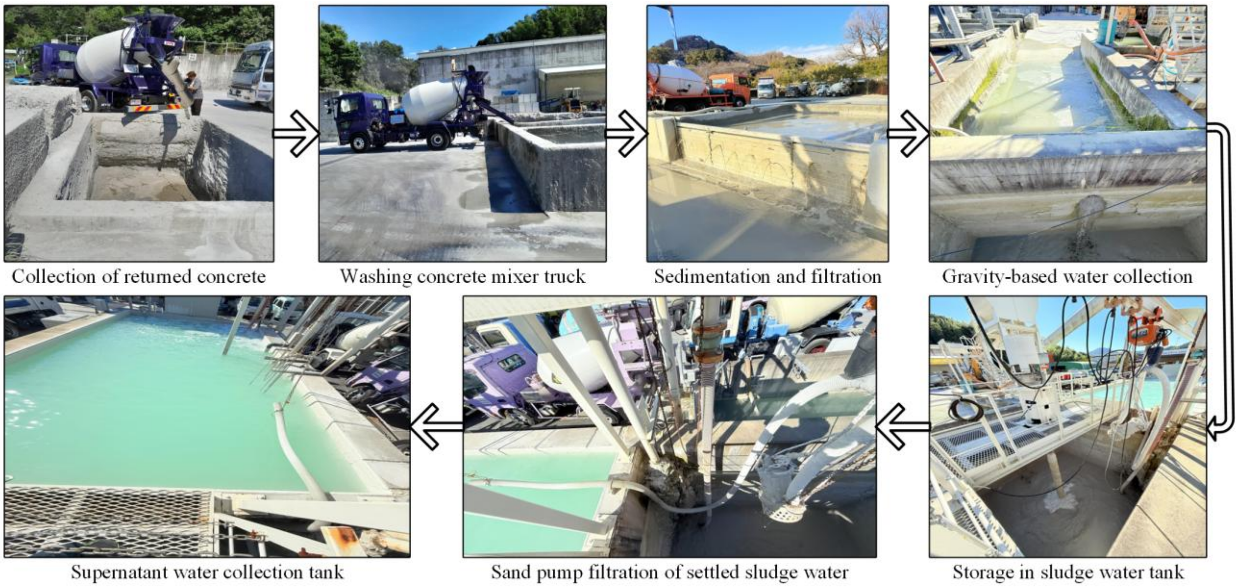


Figure 3.7 Treatment stages of supernatant water

3.2.5. Super Retardant Admixtures and Additives

The retarding admixture used in this study was geoliter 10 super retardant, a dark brown liquid composed primarily of Oxycarboxylate with a density of 1.14 g/cm³ and a pH of 11. This admixture serves a dual purpose in CLSM applications: it delays the setting time of cementitious materials while simultaneously improving workability through its dispersing effect. The dosage of Geoliter 10 is calculated as a percentage of the optimal binder content and is incorporated directly into the mixing water, with subsequent adjustments made to the total water content to maintain proper mix proportions. For soil cement applications, the recommended maximum usage is 15 kg per cubic meter, with typical dosages varying based on the desired delay duration, which can range from several hours to several days.

Pigments suitable for use with CLSM must be economically feasible. The recommended dosage, in the range of 3-6% by weight of the binder, according to Hospodarova et al. [53], was used to check the intensity. Due to the availability of red, yellow, and orange pigments at the RMC batching plant, the standard colors used to identify various types of utility lines, as per the APWA utility color code, are utilized to check color intensity. According to the APWA utility color code, red color indicates electric power lines, cables, conduit, and lighting cables; yellow color indicates gas, oil, steam, petroleum, or gaseous materials; and orange color shows communication, alarm, or signal lines; cables, or conduit.

Figure 3.8 shows geoliter 10 admixtures, measurement of its density and red color pigment color intensity at 3%, 4%, 5% and 6% of optimal binder content.

Figure 3.8 Geoliter 10 admixture, its density and color pigment

3.3. Experimental Procedure and Mix Proportions

This study presents the development of a novel, eco-friendly CLSM formulation based on the Japanese technical manual and ACI guidelines. The target performance criteria for the proposed CLSM are summarized in **Table 3.4**, in accordance with the *Technical Manual for Fluidized Soils*, with the aim of meeting the requirements for backfilling buried pipes.

The methodology employed in this study follows a systematic four-stage experimental procedure designed to develop an optimized, excavatable, and eco-friendly CLSM for backfilling buried pipes. The process begins with Stage-I, which focuses on optimizing the aggregate content by determining the ideal water-to-solid ratio that achieves the required flow (≥140 mm), wet density (≥1.40 g/cm^3), and bleeding (≤3%) properties in the fresh state. Once these parameters are verified, the methodology progresses to Stage II, where CSP is introduced as a partial replacement to optimize the filler-to-aggregate ratio, maintaining the fresh properties while beginning to assess hardened characteristics. Stage-III introduces binder content optimization, where the binder content is carefully calibrated to achieve the target

Table 3.4 General criteria for CLSM application and target performance in this study

References	CLSM Application	Criteria and Requirements to Be Fulfilled
Previously developed CLSM ACI 229R-13 guidelines	Excavatable backfilling (Underground pipelines-water, sewer, and storm drainage pipelines, roadway trench, conduit bedding)	• High degree of flowability • Self-compacting and self-leveling • Less subsidence and quick setting time • Durability properties • Easy to re-excavate—manually or mechanically • 28-day compressive strength should be ≤ 2.1 Mpa
This study adheres to the Technical Manual for Fluidized Soils in Japan along with ACI 229R-13 (Targeting performance)	Eco-friendly excavatable CLSM (Backfilling buried pipes)	• Flowability (spread of 140 mm or more) • Minimal subsidence (bleeding less than 3%) • Fresh mix wet density of 1.40 g/cm³ or more • 28-day unconfined compressive strength of 200-600 kN/m² • Backhoe excavatability 28-day strength of 500-1000 kN/m² • Hardening time [at least 130 kN/m² under roads and 50 kN/m² under sidewalks when open to traffic] • Easy to re-excavate (manually or mechanically). • Removability Modulus (RE) less than 1 • Hexavalent Chromium content 0.05mg/L or less

compressive strength (0.2-1 MPa at 28 days), removability modulus (≤1), and environmental safety (hexavalent chromium content ≤0.05 mg/L). The final Stage IV refines the mix through optimization of admixtures and additions, ensuring the CLSM meets all performance criteria including hardening requirements (at least 130 kN/m² under roads and 50 kN/m² under sidewalks when open to traffic).

This comprehensive approach, as illustrated in **Figure 3.9**, enables the systematic development of CLSM mix proportions that satisfy performance requirements while maximizing the incorporation of recycled materials and industrial by-products, thereby enhancing the environmental sustainability of the final product.

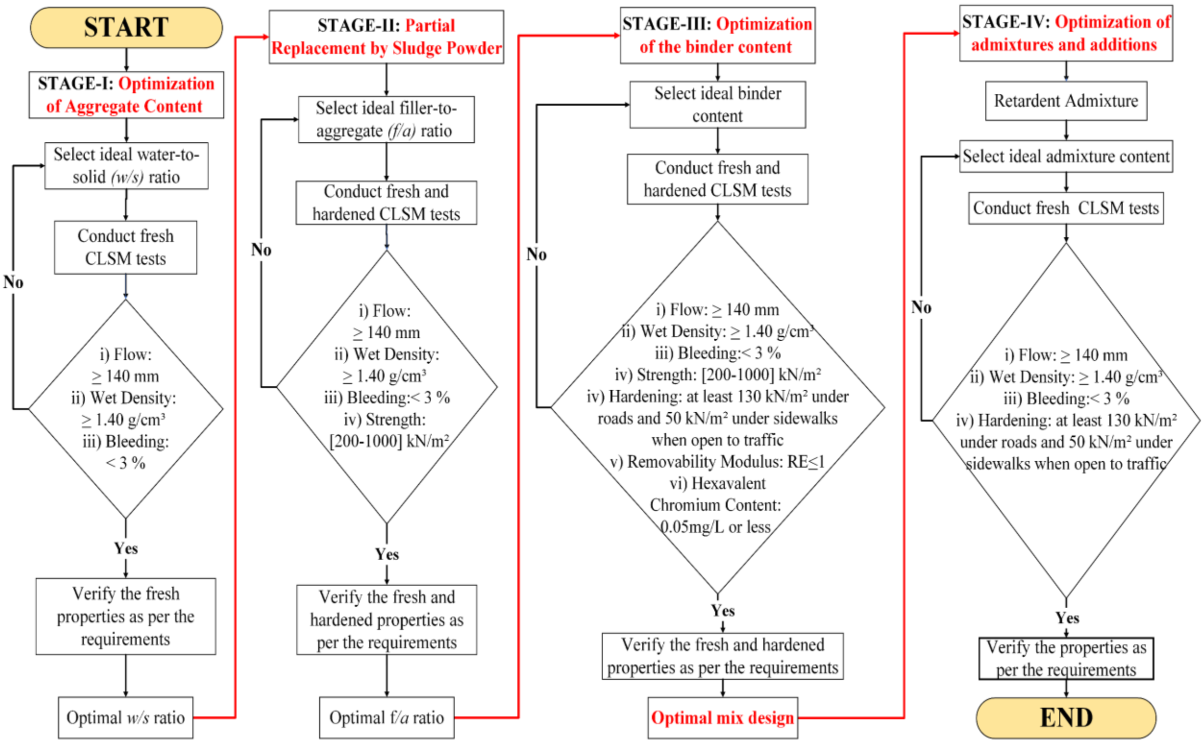


Figure 3.9 General methodology for the mix design optimization

3.3.1. Stage-I: Optimization of Aggregate Content

In this initial stage, the focus is on optimizing the granular skeleton to enhance CLSM workability and consistency. Various water-to-solid ratios (*w/s*) were tested to determine the ideal aggregate content for achieving the desired fresh properties, particularly maximum flowability. This approach ensures efficient material use by maximizing flowability and minimizing voids, guided by the water-to-solid ratio, where "solid" refers to the total mass of IWA fine aggregate and binder.

The *w/s* should be calculated through **(3.1)**, in which m_w is the water mass, m_s is the IWA fine aggregate mass and m_b is the binder mass. Alternatively, this parameter can be calculated as a function of the contents of water (v_w), fine aggregate (v_s) and binder (v_b) by volume, the densities of the water (ρ_w), specific gravity of the fine aggregate (SG_s) and specific gravity of the binder (SG_b).

$$w/s = \frac{m_w}{m_s+m_b} = \frac{v_w \times \rho_w}{v_s \times SG_s \times \rho_w + v_b \times SG_b \times \rho_w} \tag{3.1}$$

The *w/s* ratios used in this study, optimized through experimental trials, were 18%, 21%, 22%, and 24%. These ratios were carefully selected to ensure the desired workability and performance of the eco-friendly CLSM mix design. The details of the stage-I mix proportions are included in **Table 3.5**.

Table 3.5 Mixture proportions of Stage-I

w/s (%)	1m^3 of Eco-friendly CLSM mixtures in Stage-I			
	GGBFS	IWA fine aggregate	Supernatant water	Air
	(kg/m^3)			(%)
18	50	1378	264	3.9
21	50	1345	286	3.4
22	50	1315	307	2.8
24	50	1282	326	2.5

3.3.2. Stage-II: Partial Replacement by Concrete Sludge Powder

This stage explores the incorporation of sludge powder as a filler by partially replacing IWA fine aggregate. The aim is to assess the effects of sludge powder on CLSM properties, both fresh and hardened, while promoting the beneficial use of this by-product.

The *f/a* should be calculated through an equation **(3.2)**, in which m_f is the concrete sludge powder mass, and m_s is the IWA fine aggregate mass. Alternatively, this parameter can be calculated as a function of the contents of concrete sludge powder (v_f), and fine aggregate (v_s) by volume, the density of the water (ρ_w), specific gravity of the fine aggregate (SG_f) and specific gravity of the binder (SG_s).

$$f/a = \frac{m_f}{m_f+m_s} = \frac{v_f \times SG_f \times \rho_w}{v_f \times SG_f \times \rho_w + v_s \times SG_s \times \rho_w} \tag{3.2}$$

At this stage, CSP was incorporated into CLSM mixes, by replacing IWA fine aggregate at levels of 0%, 10%, 15%, 20%, and 25% by weight at each *f/a* ratios. The initial mix from Stage-I (0% replacement) serves as the baseline. The details of the Stage-II mix proportions are included in **Table 3.6**.

Table 3.6 Mixture proportions of Stage-II

	1m^3 of Eco-friendly CLSM mixtures in Stage-II				
f/a	GGBFS	CSP	IWA fine aggregate	Supernatant water	Air
(%)			(kg/m^3)		(%)
0	50	-	1315	307	2.8
10	50	131	1175	307	2.6
15	50	195	1105	307	2.5
20	50	259	1036	307	2.4
25	50	323	968	307	1.9

3.3.3. Stage-III: Optimization of Binder Content

This stage focuses on determining the minimum binder content required to achieve the target compressive strength while maintaining sufficient excavatability. The goal is to ensure that the CLSM provides adequate structural support for buried utilities yet remains easy to remove for future maintenance or repairs. To evaluate this, binder contents of 30 kg/m^3, 40 kg/m^3, 50 kg/m^3, and 60 kg/m^3 were tested to identify the optimum dosage that satisfies both strength and excavatability criteria. The investigation in this stage exclusively examines the effect of binder content, with all other parameters such as water content and *f/a* held constant.

Prior to this evaluation, the water demand of the control mix was adjusted based on findings from Stage-II, where the maximum dosage of CSP was selected within acceptable limits. Due to slag's affinity for water and its slump flow reducing characteristics water demand from Stage-II should be adjusted to make sure flow to be within limit when dosage of slag increased

Table 3.7 Extra supernatant water demand adjustment before Stage-III

Mix ID	Eco-Friendly CLSM Mixtures					Plastic Properties			
	GGBFS	CSP	IWA fine aggregate	Supernatant water	Extra water	Air (%)	Bleeding (%)		Wet density (g/cm^3)
							3hrs	24hrs	
			(kg/m^3)						
W-20	50	253	1011	307	20	2.4	1.37	0.46	1.73
W-40	50	245	979	307	40		1.40	0.47	1.71
W-60	50	237	947	307	60		3.20	2.28	1.68

to 60 kg/m³ [76]. To determine the appropriate water content, additional water was incrementally added at 20 kg/m³, 40 kg/m³, and 60 kg/m³. It was observed that when the added water exceeded 40 kg/m³, the control mixture began to segregate, and bleeding levels exceeded permissible limits 3.20%. Hence, 40 kg/m³ extra water is chosen based on plastic properties as depicted in **Table 3.7**.

Only after this water adjustment was made was the effect of binder content independently assessed, ensuring that observed changes in performance could be attributed solely to the binder dosage. The details of the Stage-III mix proportions are included in **Table 3.8**.

Table 3.8 Mixture proportions of Stage-III

Binder content	1m^3 of Eco-friendly CLSM mixtures in Stage-III					
	GGBFS	CSP	IWA fine aggregate	Supernatant water	Extra supernatant water	Air (%)
			(kg/m^3)			
30	30	247	990	307	40	2.9
40	40	246	984	307	40	2.5
50	50	245	979	307	40	2.4
60	60	243	973	307	40	2.1

3.3.4. Stage IV: Optimization of Admixtures and Additions

a) Geoliter-10 super-retardant admixture

This stage investigates the effects of admixtures and additions on CLSM properties. The primary focus is on the influence of Geoliter 10 on hardening, consistency, and workability. The methodology is adaptable to any additions and includes assessing their influence on consistency and compressive strength and evaluating specific properties conferred by the addition.

At this stage, the retardant admixture Geoliter-10 was used to evaluate its effects on hardening delay and the plastic properties of eco-friendly CLSM, considering the transportation time of ready-mixed concrete as specified in JIS A 5308, Section 9.4b, which requires delivery within 1.5 hours. At 1.5 hours, using Geoliter-10 at 0%, 2.5%, 5%, 7.5%, and 10% of binder content (40 kg/m³). The details of the stage-IV mix proportions are included in **Table 3.9**.

Table 3.9 Mixture proportions of Stage-IV

Geoliter-10 content (%)	$1m^3$ of Eco-friendly CLSM mixtures in Stage-IV					
	GGBFS	CSP	IWA fine aggregate	Supernatant water	Geoliter-10 (Binder*%)	Air (%)
	(kg/m^3)					
0	40	246	984	347	-	2.5
2.5	40	246	984	346	1	2.5
5	40	246	984	345	2	2.5
7.5	40	246	984	344	3	2.5
10	40	246	984	343	4	2.5

b) Color pigments for utility color identification

The colored pigments used in the study are sourced from the RMC company to produce the pigments. Three different types of liquid pigments in yellow, red, and brown colors were used. The recommended dosage in the range 3-6% by weight of the optimal binder content of 40 kg/m^3, by adding 1.2 kg/m^3, 1.6 kg/m^3, 2 kg/m^3, and 2.4 kg/m^3 of each color pigment on optimal mix design of Stage-III to check the intensity of the color in CLSM.

3.4. Specimen Preparation and Test Methods

The handling, mixing, and placing techniques for CLSM mirror those of conventional concrete. The mixing process begins by dry-mixing GGBFS, CSP, and IWA fine aggregate in the mixer for 30 seconds to ensure a homogenous blend and prevent lumps. Next, half of the mixing water is added and mixed for 1 minute. The mixer is then paused for 30 seconds to scrape down any adhered material before adding the remaining water (or enough to achieve the target slump) and resuming mixing for another minute. Testing for flow consistency, unit weight, and air content should commence within 5 minutes of obtaining the final composite sample. Specimen molding for strength tests should begin within 10 minutes following ASTM D 5971. This rigorous process ensures consistent, high-quality CLSM for reliable application and testing.

3.4.1. Fresh CLSM Test Methods

a) Flowability test

The flowability of the CLSM was evaluated by conducting flow tests according to the Japan Highway Public Corporation standard (JHS A 313–1992), "Test Methods for Air Mortar and

Air Milk" [77]. Measurements were conducted by filling an 80 mm x 80 mm open-ended cylinder with flowable fill on a level non-absorptive surface and then raising the cylinder quickly allowing the slurry to spread freely on the surface. When the slurry stopped flowing, the diameter of the slurry was measured in two orthogonal directions. The average diameter was recorded and defined as flowability for that composite, as shown in **Figure 3.10a**.

b) Wet density test

The constant volume method was used in this research to determine the wet density of the CLSM. A constant volume container with a capacity of 531 cm³ was filled with a freshly prepared CLSM sample, and the total mass of the sample was measured as shown in **Figure 3.10b.** The wet density was then calculated by dividing the mass of the CLSM sample by the fixed volume of the container.

c) Bleeding test

JSCE-F522 standard of “Bleeding Rate and Expansion Rate Test Method of grouting Mortar of Prepacked Concrete (Polyethylene Bag Method)” was used as the reference for bleeding test in this study. After mixing, each CLSM mixture placed in a polyethylene bag with a diameter of 50 mm and filled to a height of 200 mm. The test was done at an elapsed time of 3-hour and 24-hour after the mixing. Initial volume (V) and bleeding water volume (Vb) were measured by inserting the sample bag into 1000 mL graduated cylinder filled with water at dedicated volume scale as the measurement basis. The bleeding measurement is performed by inserting the bleeding sample bag into a graduated cylinder filled with water, then matching the water level of the sample inside the bag with water level inside the graduated cylinder. The bleeding data reading was recorded when the surface line of cement pastes inside the bleeding sample bag meets with the surface line of water of the graduated cylinder (see **Figure 3.10c**). Then, the bleeding rate is calculated by using the following equation **(3.3)**.

$$B_r = \frac{V_b}{V} \times 100 \tag{3.3}$$

where,

B_r : bleeding rate (%) after 3 hours or 24 hours

V_b : volume of bleeding water (mL)

V : volume of the specimen (mL)

d) Air content test

The air content of freshly mixed CLSM was measured using the pressure method outlined in JIS A 1128, with a slight modification. The fluid fresh CLSM was placed in a single layer without rodding, instead of in the three equal layers specified for conventional concrete [20]. The air content was then determined by reading shown on a calibrated pressure gauge, as illustrated in **Figure 3.10d.**

e) Hardening time test

This study evaluated the hardening time, which represents the estimated transition from a plastic to a hardened state for the CLSM, by following the procedures outlined in JIS A 1147, with a minor modification. Unlike conventional concrete mixes, CLSM mix was not subjected to sieving, as it is not a requirement for this material [6]. A needle penetration test, as described in **Figure 3.10e**, was conducted on the eco-friendly CLSM containing 40 kg/m^3 of GGBFS, ensuring it meets the minimum strength requirement before being opened to traffic. Hardening time can be as short as 1 hour but generally takes 3 to 5 hours under normal conditions.

a) Flowability test b) Wet density c) Bleeding rate d) Air content test e) Penetration

Figure 3.10 List of experiments conducted on fresh CLSM properties

3.4.2. Hardened CLSM Test Methods

a) Unconfined compressive strength test

Unconfined compression tests were conducted, as depicted in **Figure 3.11b**, in accordance with the JIS A 1216, "Unconfined Compression Test Method for Soil". The CLSM mixture was poured into 50 mm diameter, 100 mm high cylindrical molds. Specimens were cured at a constant room temperature of 20°C for 7, 28, 56, and 91 days [78].

b) Excavatability test

In this study a 28-day strength limit of 1000 kN/m² targeted for re-excavatability in backfilling buried pipes. According to the Technical Manual for Fluidized Soils in Japan, an unconfined compressive strength of 200-600 kN/m² is suitable for backfilling, while backhoe excavatability requires a 28-day strength range of 500-1000 kN/m². The eco-friendly CLSM developed is deemed excavatable either by manual or mechanical methods, with a target strength range of 200 to 1000 kN/m² to optimize excavatability and overall performance.

A second approach used in this study to predict excavatability follows a procedure developed and recommended by ACI guidelines in Hamilton County, Ohio. This approach uses a removability modulus (RE), as shown in the equation **(3.4)**.

- RE $\leq$ 1.0 indicates CLSM is easily removable.
- RE > 1.0 indicates CLSM is not easily removable.

$$RE = \frac{W^{1.5} \times 0.619 \times C^{0.5}}{10^6} \tag{3.4}$$

where,

i : dry mass density (kg/m^3)

C : 28-day unconfined compressive strength (kPa)

c) Permeability test

A constant head permeability test was conducted on the optimized eco-friendly CLSM, as shown in **Figure 3.11c**, in accordance with the JIS A 1108 "Soil Permeability Test Method." The specimens' mold was removed at 6 and 27 days of age, the specimens were submerged and saturated in water for one day, and measurements were taken at 7 days and 28 days of curing age. The water level difference of the test apparatus was designed to be 80 mm, and the hydraulic gradient was set to 0.4. The formula for calculating the hydraulic gradient is shown in equation **(3.5)**. This measurement is performed three times for each specimen. The flow velocity and hydraulic conductivity are calculated from the hydraulic conductivity time. The flow velocity was calculated using equation **(3.6),** and the hydraulic conductivity at the water temperature at the time of measurement was calculated using equation **(3.7)**. The hydraulic conductivity converted to permeability per 15°C of water temperature was calculated using equation **(3.8)**.

$$I = \frac{h}{L} \tag{3.5}$$

where,

i : dynamic hydraulic gradient (%)

h : water level difference (cm)

L : specimen height (cm)

$$V = \frac{Q}{A\times(t_2 - t_1)} \tag{3.6}$$

where,

v : flow velocity (cm/s)

Q : overflow per unit time (t_1 to t_2)

A : cross-sectional area of the specimen (cm^3)

t_1 : measurement start time

t_2 : measurement end time

$$K_T = \frac{v}{i} \tag{3.7}$$

where,

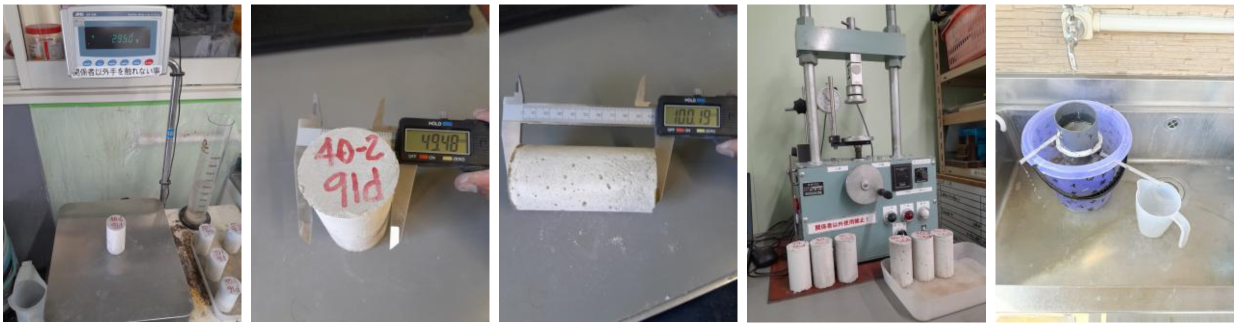
K_T : dynamic hydraulic gradient (%)

$$K_{15} = K_T \times \frac{\eta_T}{\eta_{15}} \tag{3.8}$$

where,

K_{15} : hydraulic conductivity (cm/s) when water temperature is 15°C

$\frac{\eta_T}{\eta_{15}}$: ratio of viscosity coefficient of water



a) Mass, diameter, and length measurement b) UCS test c) Permeability test

Figure 3.11 List of experiments conducted on hardened CLSM properties

3.4.3. Durability Test Methods

a) Hexavalent Chromium detection test

In this study, the Cr(VI) detection test, as described in JIS K 0102 65.2, was employed to quantify the amount of leachable Cr(VI) in the specimens of eco-friendly CLSM samples after curing for 28 days [79].

b) Wetting and drying cycles

In the present study, a 12-cycle wetting–drying test was conducted to gain a deeper understanding of the performance of CLSM under severe repeated wetting and drying conditions, in terms of mass and UCS loss. In this study, the ASTM D 599 method was used with a slight modification, where the specimens were not brushed as prescribed in the standard test method, due to the low strength of CLSM [20, 80, 81]. After the curing periods of 7, 28, 56, and 90 days, the specimens were air-dried for at least 12 hours before the wetting and drying cycles commenced. Each wet-dry cycle involved fully submerging the specimens in potable water at room temperature for 5 hours, followed by drying in an oven at 71°C for 18 hours, adopted from Huang et al, and then transferring them to room temperature to complete the drying–wetting cycle [59]. **Figure 3.12** illustrates the specimens submerged in clean water, then moved to an oven to dry, showing the deterioration of the eco-friendly CLSM specimens after completing the wetting–drying test.

To assess mass loss, twelve specimens were prepared, with three specimens tested on each of the 7, 28, 56 and 91 curing days (**Figure 3.12**). The average mass of these specimens was measured and compared to the mass of control specimens before being subjected to any wetting and drying cycles. Similarly, a separate set of twelve specimens, with three tested on each of the 7, 28, 56, and 91 curing days, was prepared to investigate the unconfined compressive strength loss. The unconfined compressive strength result without any wetting and drying cycles at Stage-IV with a binder content of 40 kg/m^3 was considered the control, and it was compared to the average residual UCS of specimens subjected to twelve wetting and drying cycles for each of the respective curing days, as depicted in **Figure 3.12**.

Figure 3.12 Wetting-drying cycles

3.5. Gradation Formulation of IWA Fine Aggregate in CLSM Mixtures

In the present study, experiments revealed discrepancies in the test results, despite being performed with the same formulation. Notably, the fresh properties exhibited excessive viscosity and material separation when using IWA fine aggregates from different sources of returned concrete. It is thought to be due to the presence of various PSDs resulting from the various aggregates in the returned concrete.

To elucidate the impact of IWA fine aggregate gradation on eco-friendly CLSM, the aggregates underwent grain size distribution analysis in accordance with JIS A 1102, “Sieving test method for aggregates.” The grain size of sand designated for concrete applications must conform to the range delineated by JIS A 5308, which specifies both upper and lower limits. A series of sieves, spanning from 10 mm to 0.15 mm, as depicted in **Figure 3.13** was employed with the IWA fine aggregate, and the sieve was subjected to manual sieving until no significant passing was observed. To investigate the effects of gradation on eco-friendly CLSM properties, eight grading zones of IWA fine aggregate were carefully selected for eco-friendly CLSM mixtures.

Figure 3.13 IWA fine aggregate gradation analysis

In the present study, the effect of gradation zone on fresh properties such as flowability, wet density, and bleeding of eco-friendly CLSM was investigated as depicted in **Figure 3.14**.

a) Flowability b) Wet density c) Bleeding d) UCS test e) Air content

Figure 3.14 List of experiments conducted at each grading zone (Center)

Table 3.10 presents the sieve analysis results for each particle size within each formulation. The IWA fine aggregate at each grading zone was incorporated into the optimized eco-friendly CLSM formulation, with details of individual sieve sizes.

Table 3.10 Effects of particle size distribution of the IWA fine aggregates

Nominal Opening of Sieve (mm)	Target the gradation curve zones							
	JIS A 5308 Center	JIS A 5308 Lower Limit	JIS A 5308 Upper Limit	① Average of LL and Center	② Average of Center and UL	③ ① and 1/2 of Center	④ LL and 1/3 of ①	⑤ Center and 1/3 of ②
10.00	100	100	100	100	100	100	100	100
5.00	95	90	100	92.50	97.50	93.75	90.83	95.83
2.50	90	80	100	85	95.	87.50	81.67	91.67
1.20	70	50	90	60	80	65.00	53.33	73.33
0.60	45	25	65	35	55	40.00	28.33	48.33
0.30	22.50	10	35	16.25	28.75	19.38	12.08	24.58
0.15	6	2	10	4	8	5	2.67	6.67

In addition to fresh properties, the present study, the effect of IWA fine aggregate gradation zone on hardened properties of the unconfined compressive strength (UCS) at 7-day and 28-day was investigated as depicted in **Figure 3.15**.

Figure 3.15 Unconfined compressive strength at 7-day and 28-day at each grading zone

3.6. Summary

This chapter presents a detailed description of the materials, mix design optimization, specimen preparation, testing procedures, and data analysis methods used in this study. The comprehensive experimental methodology ensures the reliability and validity of the results, which will be discussed in the subsequent chapter.

CHAPTER 4: EXPERIMENTAL STUDY RESULTS AND DISCUSSION

4.1. Introduction

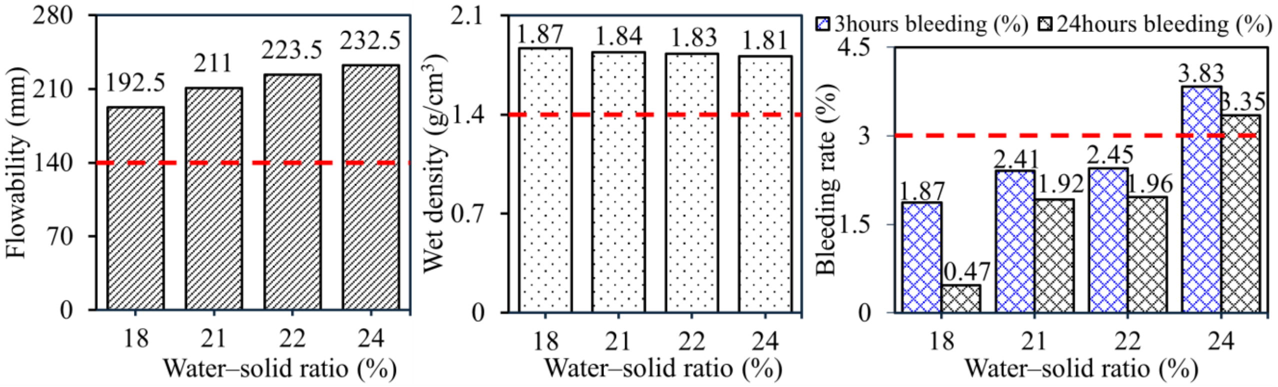
This chapter presents the findings of the four-stage experimental study regarding the properties of the eco-friendly controlled low-strength material (CLSM) mixture, as detailed in Chapter Three. It provides an in-depth discussion of the test outcomes, specifically focusing on both fresh and hardened properties, as well as the durability test results. Additionally, this section presents the effects of gradation zones of IWA fine aggregate on the tests related to fresh and hardened properties conducted on eco-friendly CLSM. These results contribute to a comprehensive understanding of the development and characterization of eco-friendly CLSM.

4.2. Stage-I: Optimization of Aggregate Content

Flow test results showed that higher *w/s* ratios increase the average flowability, ranging from 192.5 mm to 232.5 mm, as shown in **Figure 4.1a**. At all *w/s* ratios, flowability exceeded the minimum flowability requirement of 140 mm (**Figure 4.1a**).

The wet density test results indicated that as the w/s ratio increased, the fresh density of the CLSM mix decreased, reflecting higher water content and lower packing density (**Figure 4.1b**) This indicates that the solid concentration of the CLSM mix decreases as the w/s ratio increases, resulting in a decrease in the packing density of the mix. The wet density values ranged from 1.81 to 1.87 g/cm³, all exceeding the required target of 1.40 g/cm³, as depicted in **Figure 4.1b**.

Bleeding test results showed that higher *w/s* ratios resulted in an increased bleeding rate **(Figure 4.1c).** For *w/s* ratio of 0.24, the bleeding percentage was 3.83% after 3 hours and 3.35% after 24 hours, surpassing the target of 3%, as illustrated in **Figure 4.1c**. In Stage-I of the methodology, maximized flow was a primary focus to ensure adequate water content while incorporating CSP which is the filler material, and assessing its properties in subsequent Stage-II. A *w/s* ratio of 22% was determined to be the optimal mix for proceeding to the next stage of the experimental procedure. In Stage-II, the water content remains constant as established in Stage-I.



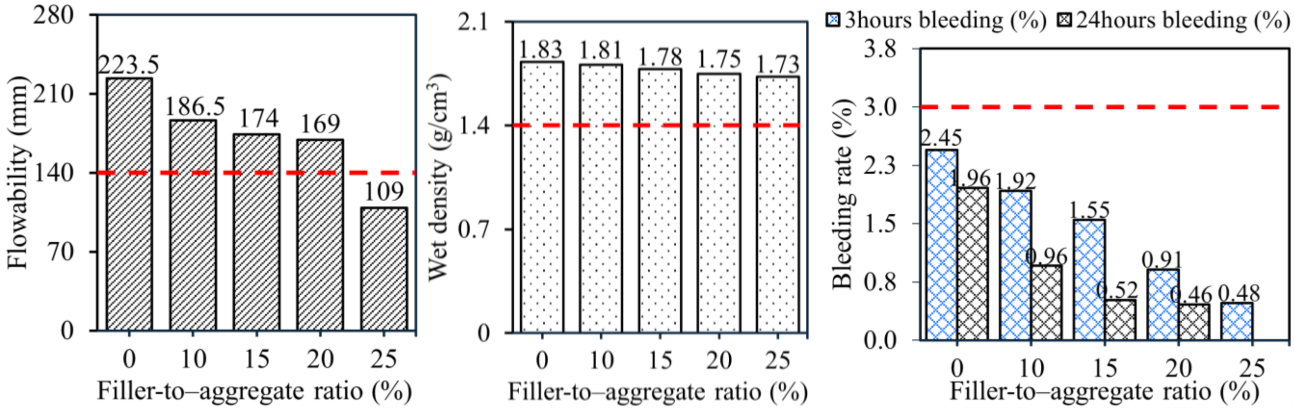
a) Effects of *w/s* on flowability b) Effects of *w/s* on wet density c) Effects of *w/s* on bleeding

Figure 4.1 Water-to-solid ratio effects on the plastic properties of eco-friendly CLSM

4.3. Stage-II: Partial Replacement by Concrete Sludge Powder

This stage investigates the effects of partially replacing IWA fine aggregate with sludge powder. The optimal *w/s* ratio of 22% from Stage-I was used as a control mix, replacing IWA fine aggregate with sludge powder. Flow tests as shown in **Figure 4.2a** revealed that increased f/a ratios led to decreased flowability, dropping from 223.5 mm to 109 mm. At a *f/a* ratio of 25%, the flow value fell below the target of 140 mm. Higher ratios required additional water for sufficient workability, affecting the control mix.

Wet density tests, as shown in **Figure 4.2b,** showed that as the f/a ratio increased, fresh density decreased, ranging from 1.83 to 1.73 g/cm³, while still meeting the requirement of 1.40 g/cm³. Bleeding rates, which indicate stability and cohesion, decreased with higher *f/a* ratios, remaining below the target of 3% after both 3 and 24 hours. The utilization of CSP effectively reduces bleeding, enhancing the eco-friendliness of CLSM, as shown in **Figure 4.2c**.



a) Effects of *f/a* on flowability b) Effects of *f/a* on wet density c) Effects of *f/a* on bleeding

Figure 4.2 Filler-to-aggregate ratio effects on the plastic properties of eco-friendly CLSM

Unconfined compressive strength tests on the specimens conducted at 7 and 28 days demonstrate an increase as the f/a ratio exceeded 10%. Interestingly, the strength slightly decreased at the 10% ratio compared to the control mix without sludge powder, suggesting that a higher proportion of the filler above 10% contributes to improved compressive strength. Furthermore, the strength results presented in **Figure 4.3**. indicate that the strength values across all f/a ratios remain within the excavatability limits, implying that excavatability can be achieved by adjusting the strength of the CLSM.

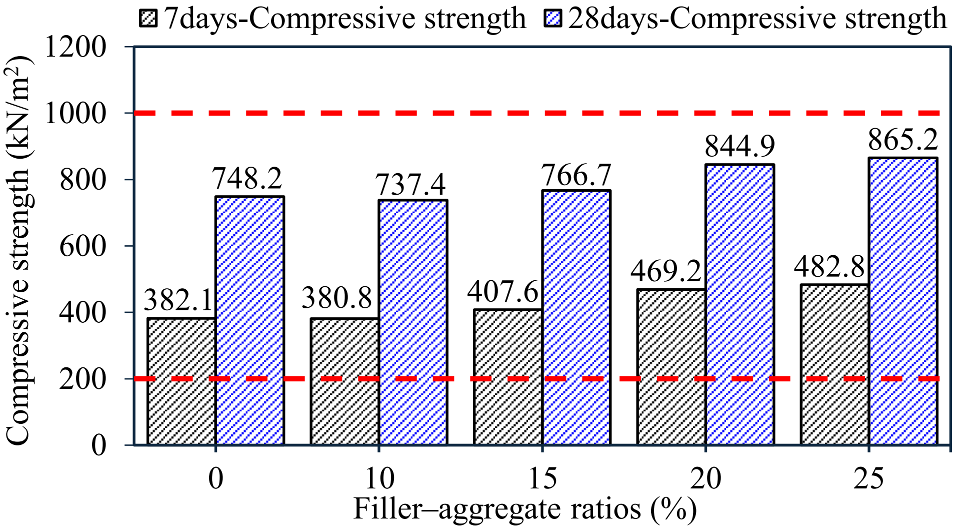


Figure 4.3 Filler-to-aggregate ratio effects on the unconfined compressive strength

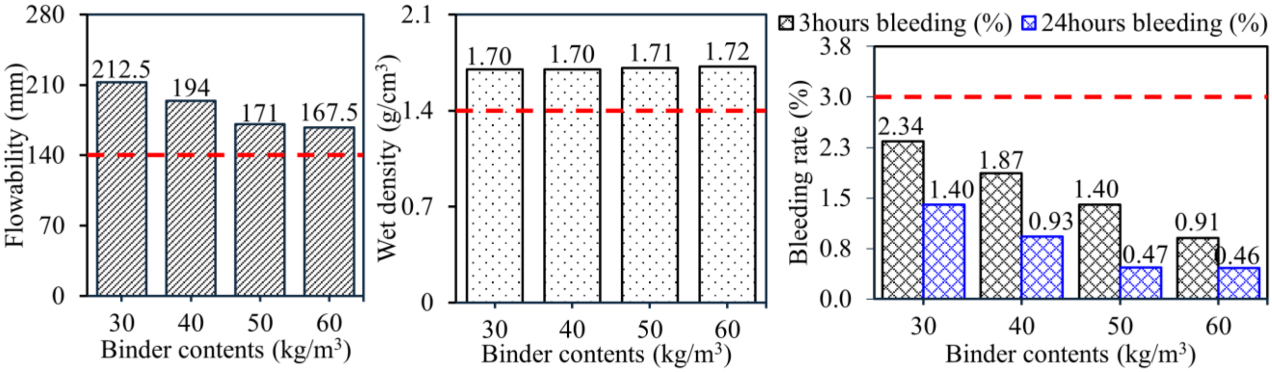
In Stage-II of the methodology, the study determined that up to 20% replacement of the fine aggregate with sludge powder could create an eco-friendly CLSM mix. The utilization of 20% sludge powder with the IWA fine aggregate was found to be an effective approach for developing a novel, eco-friendly CLSM.

4.4. Stage-III: Optimization of Binder Content

The flow test results presented in **Figure 4.4a** demonstrate a clear inverse relationship between binder content and flowability. As the binder content increased from 30 kg/m³ to 60 kg/m³, a consistent decrease in flowability was observed, with values declining from 212.5 mm to 167.5 mm. This represents a reduction of approximately 21 % across the tested range. Notably, all measured flow values remained above the target threshold of 140 mm, indicating that the mixture maintained adequate flowability across all tested binder contents.

Wet density tests, as illustrated in **Figure 4.4b**, show that as the binder content slightly increases from 30 to 60 kg/m³, the fresh density also increases from 1.70 to 1.72 g/cm³, while at all binder contents exceeding the minimum requirement of 1.40 g/cm³. This direct relationship between binder content and density suggests compositional changes that affect the material's mass-volume characteristics.

Bleeding test results showed that higher binder content resulted in a decrease in bleeding rate (**Figure 4.4c**). For a binder content of 40 kg/m³ of 0.24, the bleeding percentage was 1.87% after 3 hours and 0.93% after 24 hours, surpassing the target of 3%, as illustrated in **Figure 4.4c**. Furthermore, bleeding rates, which reflect the mixture's stability and cohesion, were observed to decline with binder content, consistently remaining below the target of 3% after both 3 and 24 hours.



a) Effects of binder on flowability b) Effects of binder on wet density c) Effects of binder on bleeding

Figure 4.4 Binder content effects on the plastic properties of eco-friendly CLSM mixtures

The experimental investigation of UCS, as depicted in **Figure 4.5** for CLSM specimens with binder contents ranging from 30 kg/m³ to 60 kg/m³, a definitive positive correlation between binder dosage and strength development is highlighted. At an early curing age of 7 days, UCS values steadily increase from 80.1 kN/m² for the 30 kg/m³ mix to 583.7 kN/m² for the 60 kg/m³ mixture. This initial phase suggests that a higher binder content accelerates early strength gain, likely due to the more rapid formation of hydration products, such as gel formation, which enhances eco-friendly CLSM matrix density and overall performance.

At 28 days of curing, a significant increase in strength is observed across all binder contents. Specifically, the UCS values rise to 137.2 kN/m², 281.9 kN/m², 835.8 kN/m², and 1007.6 kN/m² for binder contents of 30, 40, 50, and 60 kg/m³, respectively. The near-threshold strength value achieved for the 60 kg/m³ binder mix at this stage merits particular attention, as it approaches the excavatability limit, defined by the *Technical Manual for Fluidized Soils* in Japan, at 1000 kN/m². This threshold is a critical design parameter, ensuring that materials remain amenable to mechanical excavation via equipment such as backhoes.

As the curing age ranges from 56 to 91 days, the trends observed in earlier stages persist and intensify further. By 56 days, the UCS for the 60 kg/m³ mix reaches 1032.5 kN/m², and at 91 days, it ultimately increases to 1140.3 kN/m². In contrast, the lower binder content mixtures demonstrate more controlled strength development, with the 30 kg/m³ mix standing at 146.2 kN/m² (56 days) and 165.8 kN/m² (91 days), while the 40 kg/m³ and 50 kg/m³ mixes remain substantially below the excavatability limit. The differences in long-term performance suggest that managing binder content is essential not only for achieving desired mechanical properties but also for maintaining compliance with regulatory excavatability thresholds. Overall, these results underscore the importance of precise mix design in optimizing the performance and functionality of CLSM in various construction scenarios.

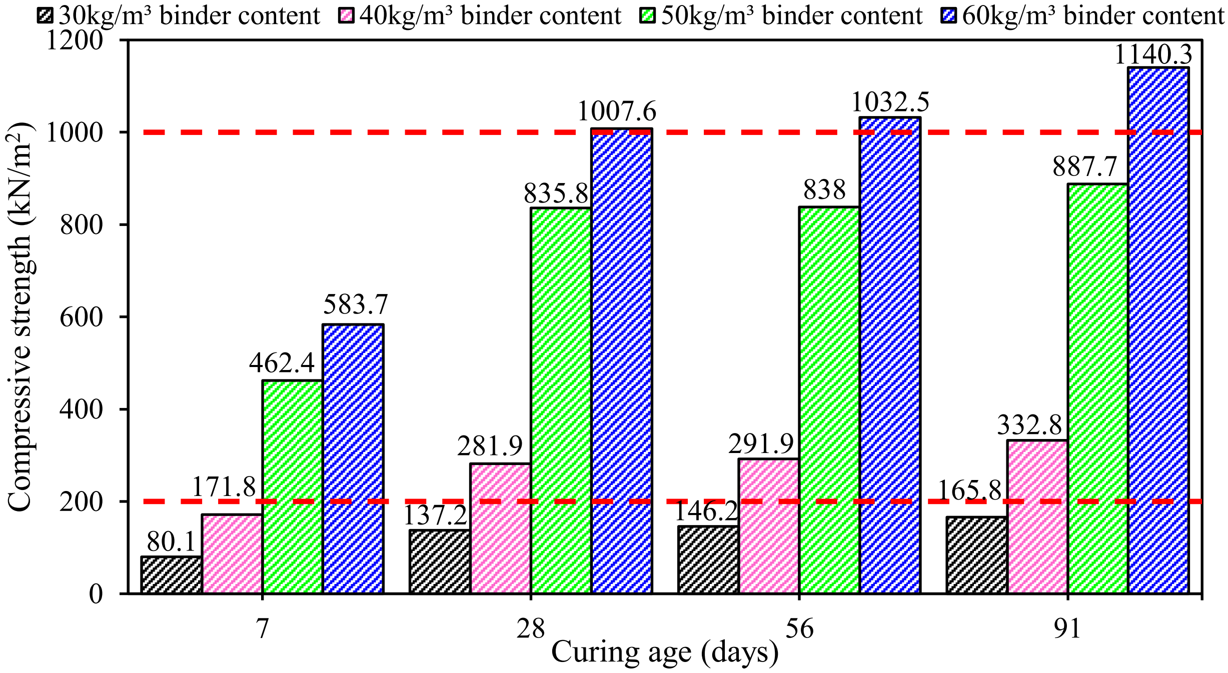


Figure 4.5 Binder content effects on the unconfined compressive strength

The present study evaluated RE values, as depicted in **Figure 4.6** at different curing periods (7, 28, 56, and 91 days), though the 28-day values serve as the standard benchmark for determining excavatability. At 28 days, the RE values were measured at 0.46 and 0.67 for binder contents of 30 kg/m³ and 40 kg/m³, respectively, both of which fell below the critical threshold of 1.0 that separates excavatable from non-excavatable materials. In contrast, the mixtures with higher binder contents of 50 kg/m³ and 60 kg/m³ exhibited RE values exceeding 1.0, indicating they would be difficult or impossible to excavate using conventional equipment. The relationship between binder content and RE values exhibits a clear positive correlation, with RE increasing in proportion to the rise in binder content.

Despite both 30 kg/m³ and 40 kg/m³ mixtures having favorable RE values below 1.0 at 28 days, the decision for optimal binder content must also consider unconfined compressive strength requirements. The 30 kg/m³ mixture, while easily excavatable with an RE of 0.46, fails to meet the required strength range of 200-1000 KN/m² for buried backfilling applications. The 40 kg/m³ mixture, with an RE of 0.67, successfully balances excavatability with adequate strength within the specified range. This makes 40 kg/m³ the optimal binder content for CLSM applications where future excavation may be necessary while maintaining structural integrity for buried utility backfilling. The study confirms that the RE calculation methodology effectively predicts field performance, with 40 kg/m³ representing the ideal compromise between strength development and future removability for practical CLSM applications.

In Stage-III of the methodology, the study determined that 40 kg/m³ can be considered as optimal binder content at which eco-friendly CLSM is excavatable . The utilization of 40 kg/m³ along with CSP and IWA fine aggregate was found to be an effective approach for developing a novel, eco-friendly CLSM.

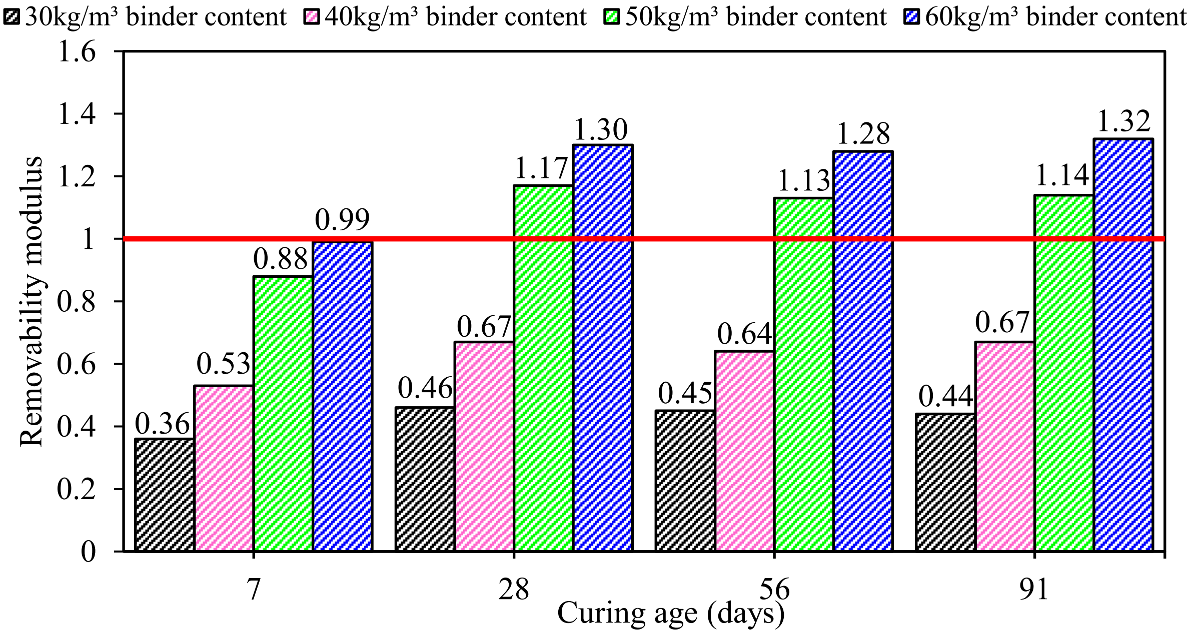
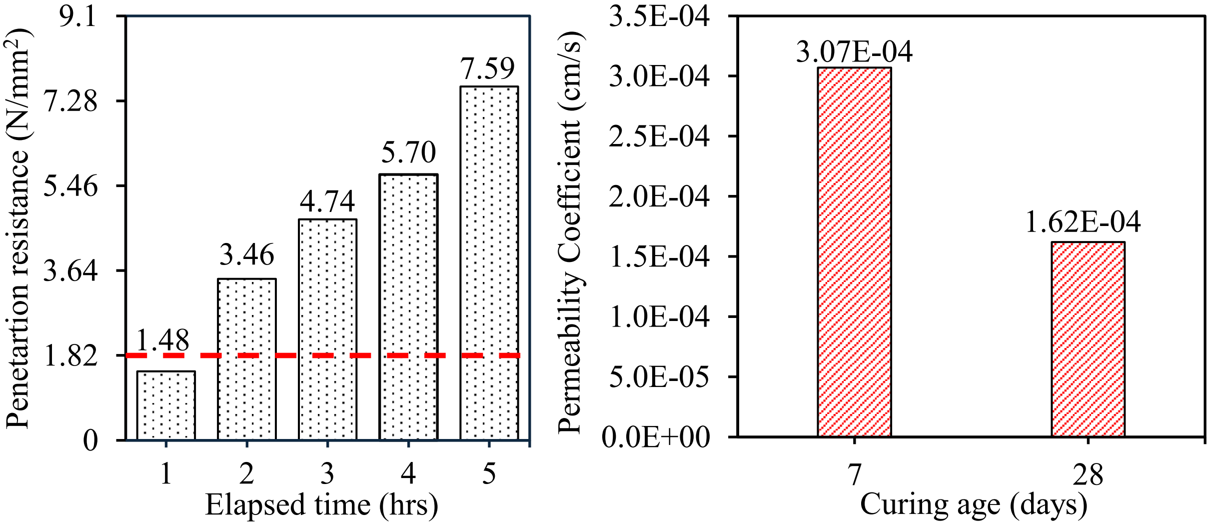


Figure 4.6 Removability modulus

As depicted in **Figure 4.7a**, the observed hardening time of 2 hours is achieved due to the improved packing density and the enhanced hydraulic activity of GGBFS in the mix. This enhancement is attributed to the acceleration by alkaline calcium hydroxide present in the supernatant water, which promotes early-age setting. Although the fluid nature of the mix complicates the direct measurement of early compressive strength, the equivalent penetration resistance provides a reliable substitute for assessing early strength development. Moreover, this rapid development allows for a quick-setting scenario, ensuring that the early-age resistance meets or exceeds the design criteria (i.e., at least 130 kN/m² for roads and 50 kN/m² for sidewalks when they are open to traffic). By targeting a penetration resistance of around 1.82 MPa at 2 hours, the study effectively demonstrates that the mix achieves sufficient early-age strength to support the placement of pavements, aligning the performance with the engineering requirements detailed in both the AASHTO and Japanese technical specifications [18, 20, 26].

In CLSM, the hydration of GGBFS is activated by calcium hydroxide and available alkalis released from residual pastes of returned concrete materials. The idea is to make use of the available alkalis and calcium hydroxide from the residual pastes in the IWA fine aggregate and CSP to fuel the hydration reaction of the GGBFS [47]. When the pH of the liquid phase reaches approximately 12, where ettringite is formed stably, the hydration of GGBFS is most accelerated. In order to maintain active hydration of GGBFS, it is necessary to supply sufficient hydroxyl (to create a high pH environment for breaking the network of glass and stabilizing the ettringite product) and SO_3 as well as alumina (to form ettringite) [82]. This hydration reaction, coupled with some hydraulic activities of GGBFS, is believed to help in hardening and strength development of the CLSM.



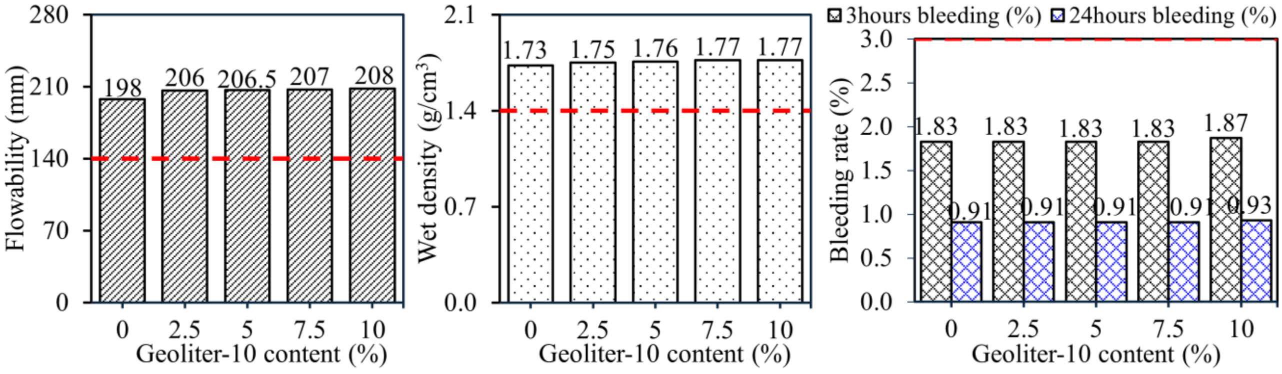
a) Hardening time b) Water permeability

Figure 4.7 Needle penetration and permeability test results

Low water permeability of CLSM is important in gas utility trenches, as it can cause water to travel along pipes until it reaches a suitable fissure, delaying leak detection. Most excavatable CLSMs have coefficient water permeability values ranging from 10^{-4} to 10^{-5} cm/s, which is similar to compacted granular fills [44]. Naik et al. [83], reported that the water permeability values of slurry mixtures decreased with the increase in age due to the improved microstructure of the CLSM matrix resulting from continuing pozzolanic reactions of wood fly ash and Class C fly ash. This study examined the permeability of the optimal eco-friendly CLSM mix with a binder content of 40 kg/m³. The water permeability values were 1.62x10^{-4} cm/sec at 7 days and 3.07x10^{-4} cm/sec at 28 days **(Figure 4.7b)**. The study observed that the hydraulic conductivity of the eco-friendly CLSM mix decreased as the compressive strength increased at both 7 and 28 days [84]. The higher strength CLSM has coefficient of water permeability values as low as 10^{-7} cm/sec [85, 86].

4.5. Stage-IV: Optimization of Admixtures and Additions

In this study, the retardant admixture geoliter-10 was used to evaluate its effects on hardening delay and the plastic properties of eco-friendly CLSM, considering the transportation time of ready-mixed concrete as specified in JIS A 5308, Section 9.4b, which requires delivery within 1.5 hours. At 1.5 hours, using Geoliter-10 at 0%, 2.5%, 5%, 7.5%, and 10% of binder content (40 kg/m³) demonstrated a significant delay in hardening. Additionally, its dispersing effect significantly enhances the workability of CLSM by reducing the viscosity of CLSM mixtures, facilitating placement in confined spaces and improving flow and wet density without significantly increasing bleeding (**Figure 4.8**). As the admixture dosage increased, the hardening time was further delayed geoliter 10 can effectively control the hardening delay of CLSM while maintaining strength (**Figure 4.9**). By adjusting the amount used, development properties without adverse effects.



a) Geoliter 10 on flowability b) Geoliter 10 on wet density c) Geoliter 10 on bleeding

Figure 4.8 Geoliter -10 content effects on the plastic properties of eco-friendly CLSM

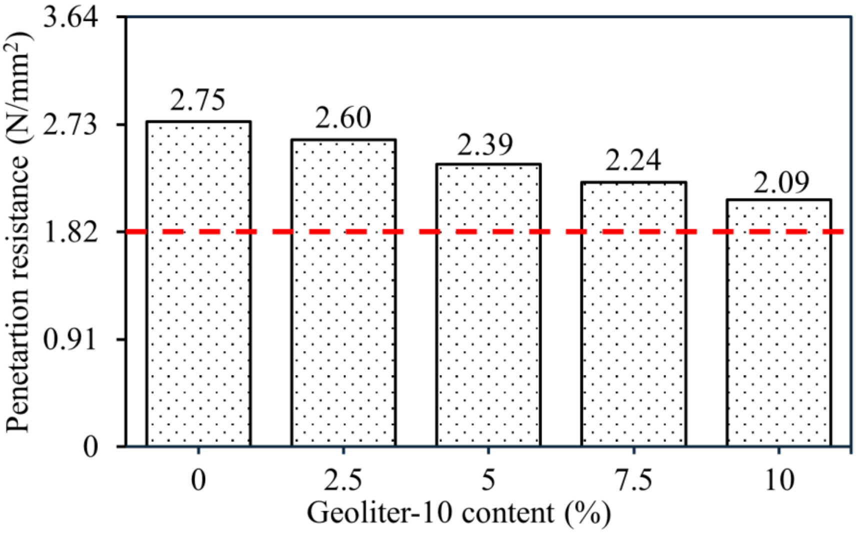


Figure 4.10 Geoliter 10 admixture effects on hardening time

The color pigment dosage range is 3-6% by weight of the optimal binder content, which is 40 kg/m³. This is achieved by adding 1.2 kg/m³, 1.6 kg/m³, 2 kg/m³, and 2.4 kg/m³ to the optimal mixture, respectively. CLSM can ensure the safety of future excavations by accurately identifying both the type and location of buried utilities. It was found that as the dosage amount increases, the intensity of the eco-friendly CLSM coloring also increases. The intensity of color at a dosage of 1.2 kg/m³ could be enough to minimize the effects of color pigment on the flowability of the CLSM mixture, as shown in **Figure 4.10**.

Figure 4.9 Color intensity of eco-friendly CLSM

4.6. Durability of Eco-friendly CLSM

4.6.1. Hexavalent Chromium Leaching Test

Minimization of Cr(VI) leaching is necessary for practical construction applications, and its level should be maintained below environmental quality standards. In this study, a Cr(VI) detection test was conducted using an eco-friendly CLSM mix with an optimal GGBFS content of 40 kg/m³. GGBFS has the capability to prevent the leaching of certain heavy metals and to immobilize Cr(VI) through a reductive process, transforming it into a less toxic form, Cr(III) [87]. As shown in **Table 4.1**, the detected Cr(VI) value in this study was 0.007 mg/L, which satisfies the environmental quality standards for soil (**Appendix A**). Furthermore, the use of GGBFS as a binder resulted in a lower Cr(VI) detection compared to previously studied CLSM mixes that utilized OPC (0.13 mg/L) and blast furnace slag cement type B (0.05 mg/L).

Table 4.1 Comparison of the leaching test for CLSM with different binders

Heavy metal elements	Detected value with different binders (mg / L)				Environmental quality standards for soil (mg / L)
	CLSM with GGBFS (this study)	CLSM with OPC [40]	CLSM with BFS cement Type B [40]	CLSM with BFS cement Type B [49]	
Cr(VI)	0.007	0.13	0.02	0.05	≤ 0.05

4.6.2. Performances after Wetting and Drying Cycles

a) Effect of wetting and drying cycles on mass loss

The mass and percentage of weight loss for the eco-friendly CLSM with the number of wetting and drying cycles at 7, 28, 56, and 91 curing days are presented in **Table 4.2**. The eco-friendly CLSM exhibited a gradual decrease in weight loss up to six cycles during the 7-day curing period, followed by a remarkable decrease as the number of cycles increased. It is noteworthy that the eco-friendly CLSM at 7 days of curing exhibited a higher weight loss compared to the other curing periods, with a maximum percentage loss of 22.04%, which is attributable to the low early strength of CLSM. To evaluate the durability of soil–cement mixtures, the Portland Cement Association (PCA) recommends criteria of a maximum mass loss of 14% after 12 cycles of wetting and drying [88]. Although this limit applies to compacted soil–cement, it is used here as a general measure of the eco-friendly CLSM's resistance to wetting and drying cycles [89].

As listed in **Table 4.2**, the eco-friendly CLSM exhibits excellent resistance to degradation at 28 days of curing. The percentage loss from the first to twelfth cycles ranged from 0.65% % to 11.77%. The tested eco-friendly CLSMs containing 40% GGBFS demonstrated high resistance to degradation, with mass loss values well below the 14% limit. The study findings demonstrated that the CLSM's resistance to repeated wetting and drying cycles was directly proportional to its compressive strength, with increased strength correlating to reduced mass loss [47, 81].

Table 4.2 Mass losses in wet-dry durability testing for eco-friendly CLSM

Measurement at each cycle	Average mass loss at each curing days			
	7 days	28 days	56 days	91 days
Original mass (g)	317.33	312.20	303.03	296.40
1st cycle (g)	315.57	310.17	300.40	294.77
2nd cycle (g)	312.17	309.33	298.13	293.40
3rd cycle (g)	309.23	308.37	297.30	293.03
4th cycle (g)	307.27	306.60	295.77	290.87
5th cycle (g)	304.13	302.83	293.83	288.50
6th cycle (g)	302.00	299.50	290.87	285.47
7th cycle (g)	295.43	295.56	287.80	280.40
8th cycle (g)	291.30	290.13	283.73	276.63
9th cycle (g)	278.37	283.30	278.87	272.23
10th cycle (g)	266.93	279.87	274.03	269.43
11th cycle (g)	256.77	277.27	271.23	266.43
12th cycle (g)	247.40	275.47	269.07	263.90
Dry mass loss (%)	22.04%	11.77%	11.21%	10.96%

b) Effect of wetting-drying cycles on unconfined compressive strength

After 12 wetting-drying cycles, the strength test results, plotted in **Figure 4.11**, indicated by the initial UCS and residual UCS at curing periods of 7, 28, 56, and 91 days of eco-friendly CLSM specimens. The UCS changes in eco-friendly CLSM under twelve wetting–drying cycles had a significant effect on the UCS. Compared to the control specimens, specimens subjected to twelfth wetting–drying showed a remarkable decrease in UCS. In zero and twelve wetting–drying cycles, the UCS decreased from 171.08 kN/m^2 to 71.04 kN/m^2, 281.90 kN/m^2 to 206.49 kN/m^2, 291.93 kN/m^2 to 218.41 kN/m^2 and 332.75 kN/m^2 to 254.76 kN/m^2, at each 7, 28, 56, 91 days respectively (**Figure 4.11**). After 12 wetting-drying cycles, the specimens exhibited a 23.44–58.65% reduction in strength compared to their counterparts without wetting-drying actions. The strength variation is that the strength reduction in terms of percentages was the largest at a 7-day curing period, 58.65%, and the trend gradually reduced with increasing curing periods.

According to PCA criteria for soil–cement mixtures, specimens pass the wetting-drying test if post-cycle strengths are 145% or more of 7-day values [89]. They fail if strengths are less than 90% of 7-day. Strengths between 90-145% of 7-days may result in either passed or failed tests, with higher probability of passing as the upper limit is approached [88]. The study findings reveal that at a curing age of 28 days, the eco-friendly CLSM can retain at least 120.2% of its original strength after 7 days, and after 12 durability cycles. This indicates that the CLSM is considered efficient and can be recommended for field applications, as it still satisfies the minimum strength requirement of 200 kN/m² for buried pipe backfilling [59].

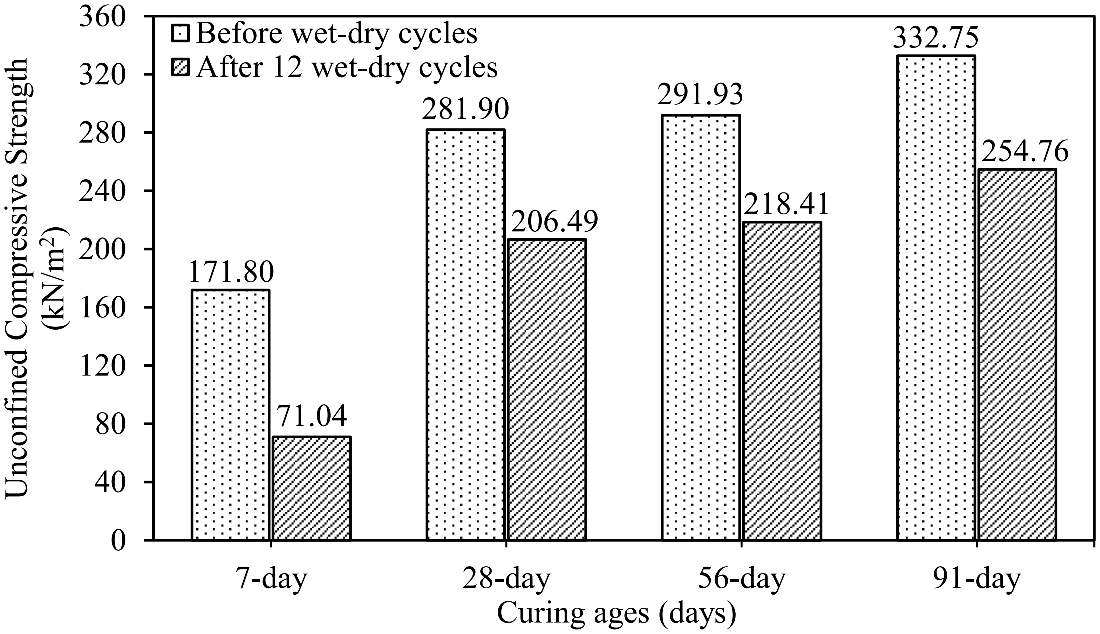


Figure 4.11 Variation of initial and residual unconfined compressive strength

4.7. Effect of IWA Fine Aggregate Gradation Zones on Eco-friendly CLSM Properties

4.7.1. Effect of IWA Fine Aggregate Gradation Zones on Fresh Properties

Table 4.3 presents experimental results on the effect of IWA fine aggregate gradation zone on the fresh properties of eco-friendly CLSM. It is observed that the IWA fine aggregate, confirming the lower limit gradation zone, shows the highest flow of 266 mm compared to other gradation zones at constant quantities of IWA aggregate. When the gradation curve of the IWA fine aggregate is close to the upper limit part of the curve map, the overall trend of flowability is declining. The influence of the fineness modulus and gradation zone of IWA fine aggregate on the flowability of eco-friendly CLSM is shown in Aggregates. **Table 4.3** presents the average flow value of eco-friendly CLSM is approximately linearly proportional to the fineness modulus of IWA fine aggregate. This is due to the IWA fine aggregate at the lower limit gradation zone, which contains coarser particles and has a lower surface area compared to other gradation zones, requiring additional water to achieve the same flowability. That means flow reduces with increased surface area, as clearly observed for all gradation zones, ranging from the lower limit to the upper limit of the IWA fine aggregate.

Similarly, flow can increase with an increase in fineness modulus (**Table 4.3**). That means that the flow is directly proportional to the fineness modulus as well as the grading zone of the IWA fine aggregate. This is because, for samples with a low fineness modulus, there are more small particles in the IWA fine aggregate; the content of eco-friendly CLSM paste is not enough to cover and bind these particles. Therefore, the flowability of the eco-friendly CLSM decreases because of the shortage of the paste. For the gradation curve near the lower part of the curve map, the content of fine particles is less than the content of coarse particles. Finer aggregate gradations require a greater amount of water to produce a similar level of CLSM flow, overcoming the increased friction between particles.

Table 4.3 Effects of particle size distribution of the IWA fine aggregate

Target gradation limit	Properties				Fine modulus (FM)	Freshness Properties
	Wet density (g/cm^3)	Average flow (mm)	Bleeding(%)			
			3 hours	24 hours		
Lower Limit	1.63	266.00	3.57	3.20	3.43	Material Separation
No.④	1.62	246.00	2.45	1.96	3.31	Good
No.①	1.62	223.50	1.92	0.96	3.07	Good
No.③	1.59	218.00	1.55	0.52	2.89	Good
Center	1.58	202.50	1.40	0.47	2.72	Good
No.⑤	1.58	192.00	1.37	0.46	2.60	Good
No.②	1.55	181.00	1.44	0.48	2.36	Good
Upper Limit	1.52	138.00	0.89	0.45	2.00	Excessive Viscosity

It is observed that the IWA fine aggregate conforming to the lower limit grading zone gives higher wet density than other grading zones (**Table 4.3**). IWA fine aggregates have a better degree of particle packing due to the availability of various aggregate sizes within them. An uncompacted void is reduced to a greater extent due to the proper grain size distribution in a mix. Furthermore, the filling effect and seeding effect of fine particles in sands are two possible mechanisms in CLSM that could fill voids in the matrix and make it denser.

In the present study, it also examined how gradation affects the bleeding rate. As the target limit narrows toward the upper limit, the material becomes more segregated, resulting in increased bleeding rates at 3 and 24 hours (**Table 4.3**). In this experiment, the appropriate physical property of the eco-friendly CLSM was determined from the flow value and fresh properties, but the wet density and bleeding rate, which are other physical properties required for the fluidized soil, were within the standard values. The most severe fresh property that can be affected by a property item is the flowability.

4.7.2. Effect of IWA Fine Aggregate Gradation Zones on Compressive Strength

Figure 4.12 presents the 7-day and 28-day unconfined compressive strengths of eco-friendly CLSM prepared using the specified IWA fine aggregate proportion at different gradation zones. In 28-day strength at all gradation zones, the UCS of each mixture lies within the range of requirements for the backfilling of buried pipe applications. It was clearly confirmed that as

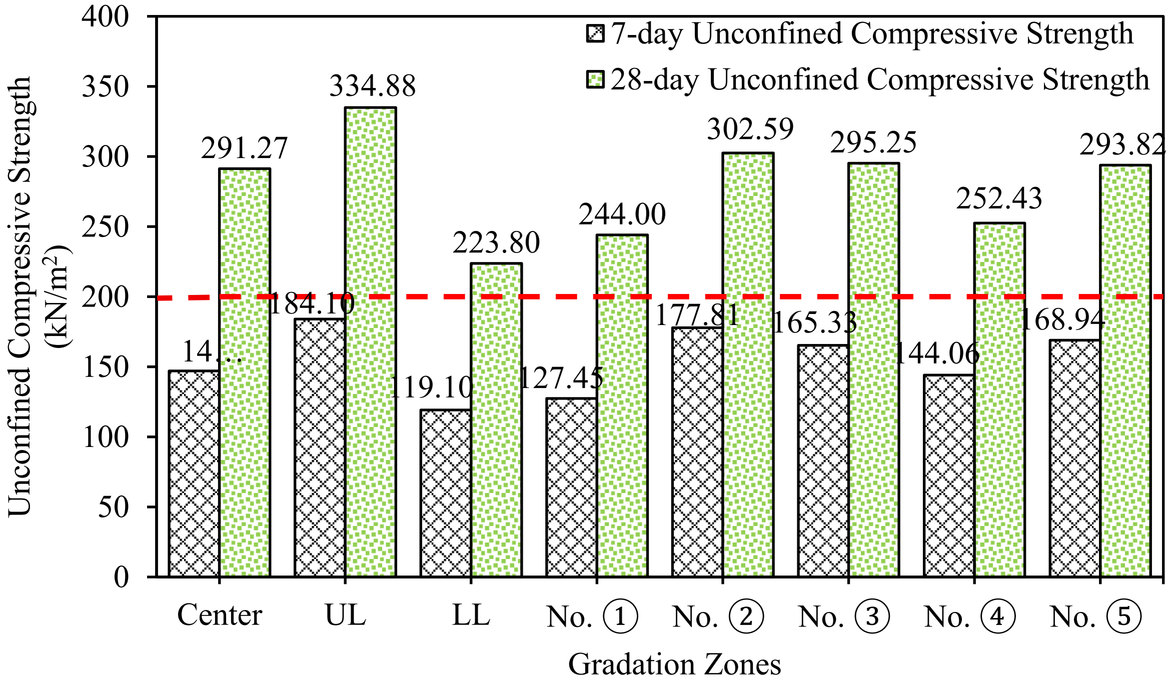


Figure 4.12 Effect of Gradation Zone on the Unconfined Compressive Strength

the fineness modulus of fine aggregate in the mix increases, the unit mass increases, and the flow value decreases accordingly, while the unconfined compressive strength does not have a linear relationship with FM.

An experimental study indicated that the properties of IWA fine aggregate, such as gradation and angularity, dictate the mixture proportions required to achieve flow, wet density, and bleeding characteristics, and therefore indirectly influence the suitability time for load application and the development of compressive strength. Hence, the main properties, such as compressive strength, bleeding rate, and unit volume mass, were measured at each gradation zone, from the upper to the lower limits of the particle size curve, to determine the appropriate flow value and fresh properties in the eco-friendly CLSM. From these results, it was found that eco-friendly CLSM with appropriate properties can be produced by using IWA fine aggregates within the particle size curve ranges of ② and ④, as shown in **Figure 4.13**.

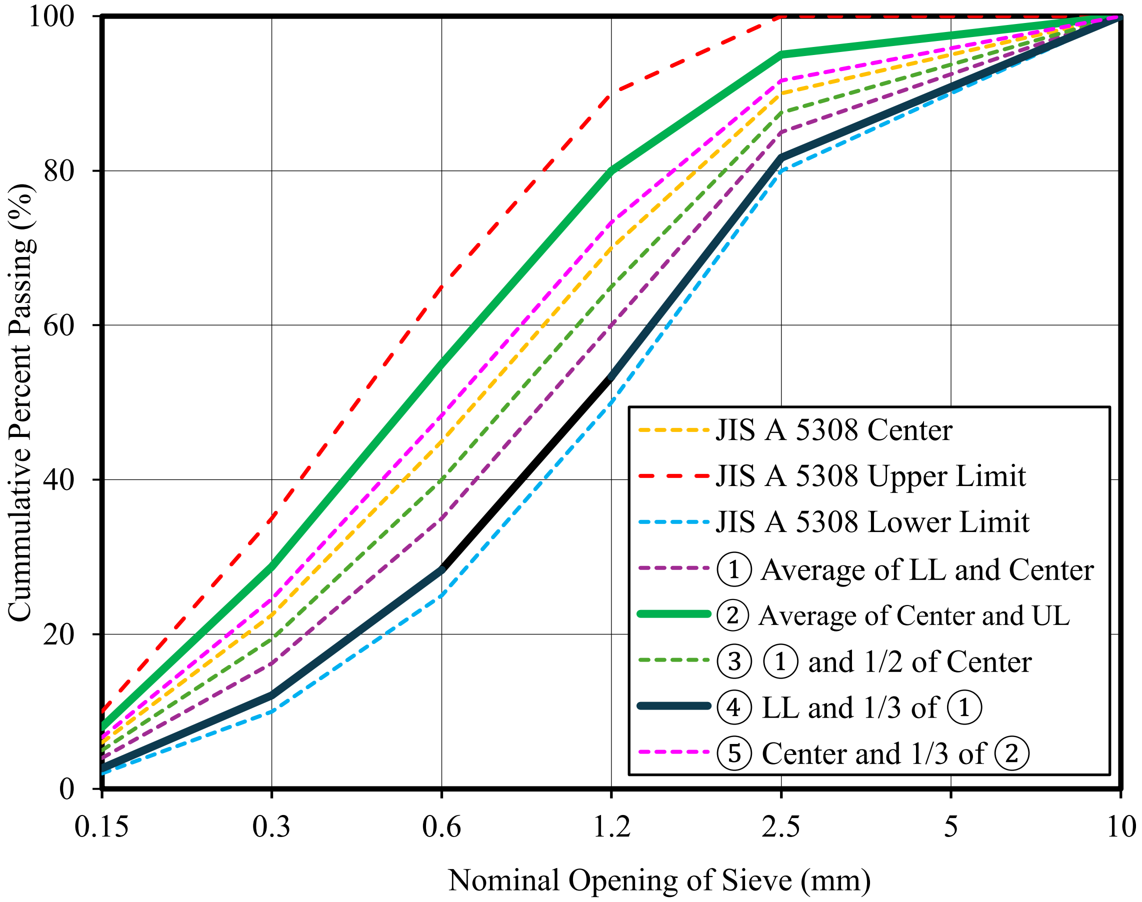


Figure 4.13 IWA fine aggregate gradation zone in eco-friendly CLSM

4.8. Eco-friendly CLSM Scanning Electron Microscopy Observation

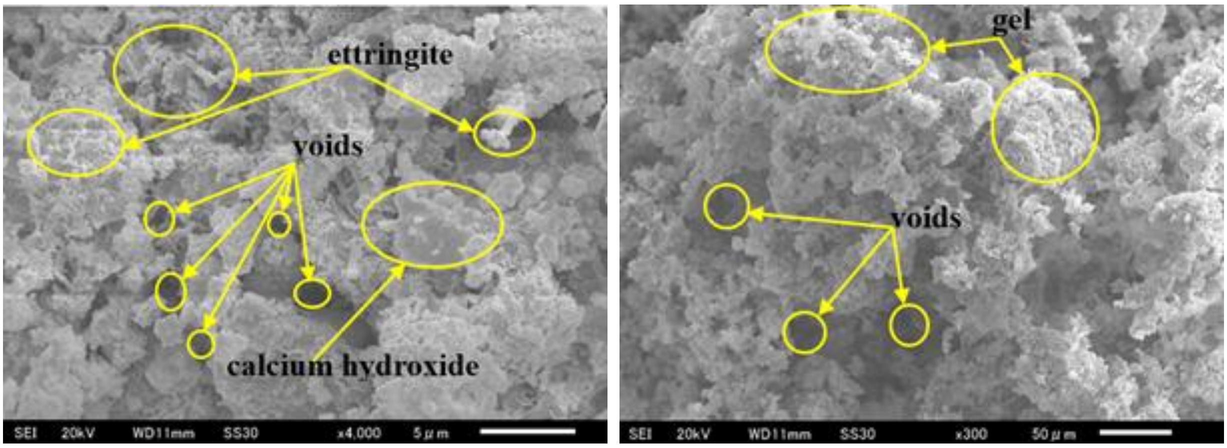
The morphological characterization of the CLSM was conducted using Scanning electron microscopy (SEM) to investigate the evolution of hydration products in eco-friendly CLSM across 7-day and 28-day curing periods. A JSM-6010LA, manufactured by Japan Electron Optics Laboratory (JEOL) Co., Ltd., was used to observe the coated specimens at an acceleration voltage of 20 kV, with a 5 µm resolution, to ensure optimal image resolution. The resulting images revealed hydrates, voids, and gel with different morphologies and sizes, reflecting the progression of hydration and its effect on microstructural development.

The SEM images of eco-friendly CLSM at curing ages of 7 and 28 days are shown in **Figure 4.14a** and **Figure 4.14b**. Initially, at 7 days, small, needle-like ettringite crystals form as a result of the hydration of the aluminate phase. During the 7-day curing period shown in a, a notable amount of flake-like calcium hydroxide is observed, mainly in regular, straight hexagonal shapes with clear boundaries, as depicted in **Figure 4.14a**. This phenomenon occurs due to the dissolution process that follows the mixing of GGBFS, IWA fine aggregate, and CSP with supernatant water rich in $Ca(OH)_2$. In the SEM analysis, smoke-like hydrates, believed to be gel, were also seen. The gel, which primarily contributes to strength, fills the spaces between the ettringite crystals, resulting in a denser structure and enhancing strength at later stages of curing [46, 47]. Moreover, the results for 28 days of curing indicate that the gel appears to have penetrated the gaps between the ettringite hydrates, likely leading to a denser hydrate structure, which may have contributed to the increase in strength [47].

In the SEM performed, smoke-like hydrates, which are thought to be gel, were observed. In particular, the results for the 28-day curing period indicate that the gel formation appears to have penetrated the gaps between the ettringite hydrates. This is thought to have resulted in a denser hydrate structure, which may have affected the increase in strength [72]. After hydrating for 7 days, many voids were found on the surface of the eco-friendly material compared to 28 days, probably due to the existence of a porous structure, similar to a honeycomb, in the CSP particles, which mainly contain $Ca(OH)_2$, fine sand, and cement hydrates [14].

The images in **Figure 4.14b** reveal that unreacted CSP microspheres are embedded in the gel phase and the IWA aggregate. The presence of CSP microspheres is attributed to the high calcium and silica content in the system. With the increase in curing ages, the microspheres of CSP gradually decreased in size, and the microstructure of the sample became more regular.

The density of the matrix was significantly increased, with fewer voids appearing. This is because, as the curing age increases, GGBFS and other materials in the sample continue to undergo hydration reactions. Moreover, the CSP promotes the hydration reaction, and the pore-filling effect makes the structure denser.



a) 7-day eco-friendly CLSM SEM

b) 28-day eco-friendly SEM

Figure 4.14 Eco-friendly CLSM SEM observation

4.9. Summary

This chapter presented a detailed description of life cycle assessment methods, including goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation. Additionally, life cycle costing analysis methodology, including rate analysis of direct costs such as materials, labor, and equipment, is explained. The comprehensive life cycle assessment and life cycle costing analysis ensure the reliability and validity of the results, which will be discussed in the subsequent chapters.

CHAPTER 5: LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING

5.1. Introduction

The construction sector significantly contributes to global pollution, accounting for 38% of energy-related greenhouse gas emissions [90]. The reliance on virgin materials in concrete production accelerates resource depletion, environmental pollution, and global warming. Disposing of returned (RC) in landfill sites has a heavy impact on the environment, which may be expressed in terms of equivalent CO_2, the gas mainly responsible for global warming, with an effect of 267 kg of CO_2 per cubic meter of RC [13]. Furthermore, recycling one cubic meter of RC with the special admixture generates only 6.75 kg of CO_2, which is nearly 40 times less than the emissions associated with disposing of it in a landfill. Moreover, apart from these, there are also corresponding advantages associated with a significant reduction in costs for production, the acquisition of raw materials, and the disposal of RC waste [13].

The increasing global focus on sustainable construction practices has led to considerable investigation into the application of industrial byproducts and recycled concrete waste. Conventional CLSM typically consists of small amounts of cement, fine aggregates, and a large amount of mixing water [18]. The tremendous environmental concern lies in the fact that ordinary Portland cement (OPC) is responsible for a significant portion of global CO_2 emissions, with its production being a major contributor, accounting for up to 8% of the total anthropogenic CO_2 emissions [91].

More studies have been conducted to develop cementless CLSM using only recycled and by-product materials without the need to add OPC. Achtemichuk et al. successfully developed a sustainable construction material, CLSM, utilizing fine and coarse recycled concrete aggregate (RCA) with slag or fly ash, without the use of OPC, and achieved a 28-day compressive strength of 7.2 MPa [47]. In addition, Do et al. successfully developed the cementless CLSM using the quaternary blends of lime, fly ash, red mud, and gypsum, and the 28-day strength ranged from 2.2 to 4.5 MPa [92]. Furthermore, Lee et al. suggested using alkali-activated slag and fly ash as the cementing material to produce OPC-free CLSM, which exhibited a compressive strength of 1.0 to 2.0 MPa at 56 days [93]. Moreover, Xiao et al. successfully developed a cementless CLSM based on the pozzolanic reaction between waste glass powder and hydrated lime, achieving a compressive strength of up to 1.95 MPa [94]. In our previous study, we successfully developed the cementless CLSM using the RC fully recycled materials by partially replacing IWA fine aggregate with concrete sludge powder (CSP) along with ground granulated blast-furnace slag (GGBFS) as a binder, and the study demonstrated that utilizing 20% CSP as a filler was a practical approach for developing a novel, eco-friendly CLSM [95].

Josa et al. [90] assessed the economic and environmental implications of trench construction through Life Cycle Costing and Life Cycle Assessment, examining four scenarios: classical solution (CS) involving landfill disposal of excavated materials, classical solution with on-site soil reuse (CS+R), the utilization of controlled low-strength material (CLSM) fluid mortar, and an eco-trench (ECO) approach that reuses extracted material up to 0.15 m from the surface, completing the fill with slightly expansive concrete (**Figure 5.1**). The findings indicated that the eco-trench system, which maximizes material reuse, could decrease environmental and economic impacts by over 80% and 50%, respectively.

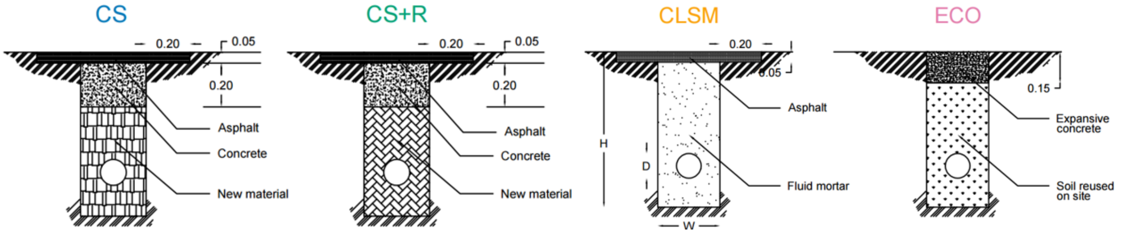


Figure 5.1 The four types of trenches considered in the analysis

Researchers have also attempted to utilize various waste materials and industrial by-products, such as fly ash, foundry sand, GGBFS, bottom ash, cement kiln dust, steel slag, waterworks sludge, paper sludge, waste rubber tires, and red mud, for developing eco-friendly CLSM [12, 42, 96-98]. It has been well acknowledged in earlier studies that the utilization of waste materials and industrial by-products will contribute to making CLSM low-cost and environmentally friendly. However, besides a comprehensive investigation on the development of sustainable CLSM life cycle assessment (LCA) and life cycle cost (LCC) of this developed sustainable material, which indicates environmental impacts and economic aspects of eco-friendly CLSM with conventional CLSM and granular compacted backfill material, has been explored less [99-101].

To address these limitations, further quantitative research is required to assess the environmental impacts and economic analysis of eco-friendly CLSM in comparison with conventional CLSM and conventional granular compacted backfilling throughout their life cycles. This research investigates the feasibility of producing eco-friendly CLSM for buried pipe backfilling entirely from recycled RC and industrial by-products, minimizing environmental impact while promoting resource efficiency. LCA can be utilized to assess the environmental effects of backfilling materials, considering different stages of scenarios during extraction, transportation, production, and installation stages.

This research study employed midpoint-based LCA and LCC to compare the environmental impacts of conventional CLSM, eco-friendly CLSM, and conventional granular compacted backfilling alternatives. A comparative LCA was performed using the ReCiPe 2016 Midpoint (H) life cycle impact assessment method in the OpenLCA software. LCC considered only a direct cost analysis, conducted based on the unit price collected from ready-mixed concrete (RMC) companies and the labor price of Shizuoka Prefecture, utilized in the rate analysis. Therefore, this study will be helpful for RMC companies and contractors in facilitating their decision-making process for selecting a more sustainable CLSM.

5.2. Materials

5.2.1. Eco-Friendly CLSM

In this study, an industrial by-product, GGBFS 4000 specified in JIS A 6206, was utilized as the binder for eco-friendly CLSM. According to the emission inventory data utilized, the environmental impacts used per ton of GGBFS were 26.5 kg CO_2 (carbon dioxides) equivalent, 0.00836 kg SO_x (sulfur oxides) equivalent, 0.0102 kg NO_x (nitrogen oxides) equivalent, and 0.00169 kg PM (particulate matter) equivalent alongside emission due to energy used for operation [102, 103].

The IWA fine aggregate utilized as fine aggregate in eco-friendly CLSM was obtained from the RMC plant in Shizuoka Prefecture. Considering the emissions generated by recycling with a special admixture of 6.75 kg of CO2, and the production of 2.3 tons of new IWA aggregates from one cubic meter of returned concrete, the environmental impacts per ton of IWA Fine aggregate used in this study are 2.81 kg CO_2 equivalent. The remaining emission data for the recycled aggregate type III treated in situ were 0.00120 kg SO_x equivalent, 0.0164 kg NO_x equivalent, and 0.00119 kg PM equivalent. Additionally, the emissions during the mechanical sieving process to separate the fine and coarse IWA aggregates were considered as energy consumption during the operation [13, 102].

In the present study, CSP sourced from the RMC plant in Okayama Prefecture and Shizuoka Prefecture was utilized as a filler in eco-friendly CLSM. Concrete sludge waste generated at concrete plants is collected in sedimentation pits and dewatered to reduce moisture content. The dried sludge cake is then crushed mechanically into a fine powder. The dust collection system is employed to separate the fine CSP particles from the coarser sludge sand. The collected CSP is then packed and stored in unopened bags under cool and dry conditions. According to data from Taiheiyo Cement Corporation [104], the amount of CO_2 absorbed in one ton of solid CSP was 208 kg. Emission during the production of CSP by the impact crusher is considered as energy during the operation of the impact crusher (1.23 kWh/t) and for sieving (0.25 kWh/t) were used [102].

Supernatant water, recycled from concrete washing wastewater at the RMC plant in Shizuoka Prefecture, was employed as the mixing water for CLSM mix. This supernatant water has a density of 1.0 g/cm^3 and a pH of 11. As a byproduct of washing leftover concrete, the supernatant water contains a significant amount of calcium hydroxide. The amount of carbon emissions for wastewater from the previous study was considered for supernatant water as equivalent to the emission due to washing of the concrete truck and filtration process using a sand pump to collect into the final tank was 0.0576 kg CO_2/m^3 [105]. **Table 5.1** presents the eco-friendly CLSM mix proportions in volumetric terms and per unit length of trench.

Table 5.1 Eco-friendly CLSM mix proportions

Mix-ID	Eco-friendly CLSM mix proportion by weight				
	GGBFS	IWA fine aggregate	CSP	Supernatant water	Air
	1m^3 of Eco-friendly CLSM (kg/m^3)				(%)
Eco-friendly CLSM	40	984	246	347	2.5
	Eco-friendly CLSM in 1m length of trench (kg/m)				
	44	1087	272	383	

5.2.2. Conventional CLSM

The binding material used in the conventional CLSM mixture for this study was OPC, conforming to JIS R 5210, possessing a density of 3.16 g/cm^3 and a specific surface area of 3340 cm^2/g. According to the emission inventory data, the environmental impacts per ton of OPC were 766.6 kg CO2 equivalent, 0.122 kg SOx equivalent, 1.55 kg NOx equivalent, and

0.0358 kg PM equivalent, in addition to emissions resulting from the energy used for operation [102, 103].

Quarry sand was used as fine aggregate for the conventional CLSM mix, and it was obtained from a local source primarily due to its local availability. Its physical properties, such as specific gravity, water absorption, unit volume mass, and fine particle mass, are presented in **Table 5.4**. According to the emission inventory data, the environmental impacts used per ton of sand were 3.7 kg CO2 equivalent, 0.00860 kg SOx equivalent, 0.00586 kg NOx equivalent, and 0.00199 kg PM equivalent, alongside emissions due to energy used for operation [102, 103].

Drinking tap water, free of any organic matter and complying with JIS A 5308, was used as mixing water for conventional CLSM. The amount of carbon emissions for tap water considered was the CO_2 emission factor 0.59 kg CO_2/m^3, as announced by the Environment Agency of Japan, which was used. [106]. **Table 5.2** presents the conventional CLSM mix proportions in volumetric terms and per unit length of trench.

Table 5.2 Conventional CLSM mix proportions

Mix	Conventional CLSM mix proportions by weight			
	OPC	Fine aggregate	Tap Water	Air
Conventional CLSM	1m^3 of Conventional CLSM (kg/m^3)			(%)
	40	1604	347	2.8
	Conventional CLSM in 1m length of trench (kg/m)			
	44	1772	383	

5.2.3. Compacted Granular Compacted Fill

For granular compacted backfill, two types of Class-I granular materials were selected as ASTM D 2321 [68]. Well-graded gravel with a maximum particle size of 20 mm was considered for the bedding layer. It was obtained from a local source primarily due to its local availability, and its physical properties are presented in **Table 5.3**. According to the emission inventory data, the environmental impacts used per ton of gravel were 2.9 kg CO_2 equivalent, 0.00607 kg SO_x equivalent, 0.00415 kg NO_x equivalent, and 0.00141 kg PM equivalent, alongside emissions due to energy used for operation [102, 103].

In the pipe embedment zone, initial and final layers of Class I well-graded sands (SW) were used. To enhance placement around small diameter pipes and prevent damage to the pipe wall, use sand with a maximum aggregate size of 5 mm and a maximum fine aggregate content. Based on the USCS soil classification system, the quarry sand is classified as well-graded (SW), with a coefficient of uniformity (Cu) of 6.11 and a coefficient of curvature (Cc) of 1.06.

According to the emission inventory data, the environmental impacts used per ton of sand were 3.7 kg CO_2 equivalent, 0.00860 kg SO_x equivalent, 0.00586 kg NO_x equivalent, and 0.00199 kg PM equivalent, alongside emissions due to energy used for operation [102, 103]. **Table 5.3** presents the granular compacted backfilling mix proportions in volumetric terms and per unit length of trench.

Table 5.3 Granular compacted backfill mix proportions

Mix-ID	Granular compacted backfill mix proportions by weight		
	Quarry Sand	Quarry Gravel	SPD
	1m^3 of Granular compacted backfill (kg/m^3)		%
Granular compacted backfilling	2577	175	95
	Granular compacted in 1m length of trench (kg/m)		
	4277	291	

Physical properties of fine aggregate from quarry sand and gravel are considered as granular compacted backfilling materials, such as specific gravity, water absorption, unit volume mass, and fine particle mass, are presented in **Table 5.4**.

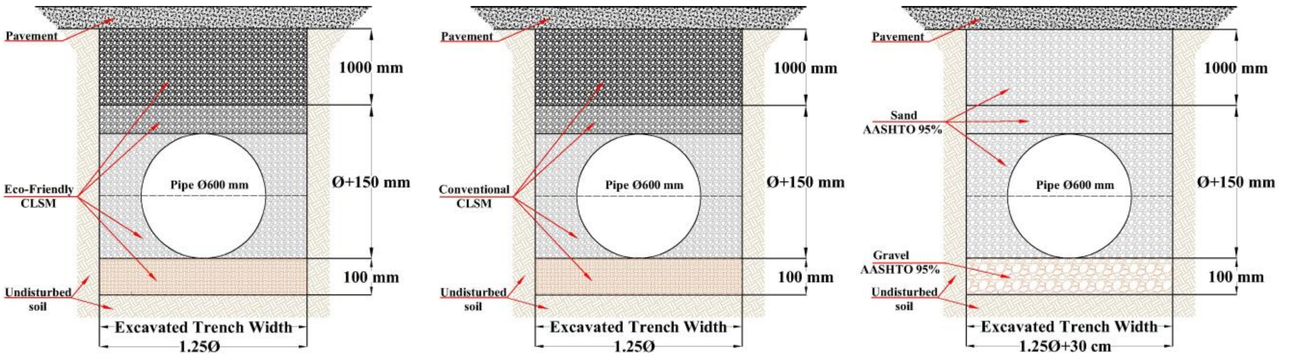
Table 5.4 Physical properties of the granular materials used in this study

Types of Aggregates	Physical properties				
	Surface dry density (g/cm^3)	Oven-dry density (g/cm^3)	Water absorption rate (%)	Unit volume mass (kg/l)	Fine particle content (%)
Fine aggregate	2.62	2.59	1.2	1.71	1.2
Gravel	2.64	2.61	0.73	1.62	0.1

5.2.4. Trench Cross-Section Details for Utility Buried Pipes

The calculations related to the trench cross-section details characteristics and the volumes to be excavated and backfilled were estimated using the guidelines proposed in ASTM D2321 and alongside Plastics Pipe Institute (PPI) Installation and Construction Procedures guidelines [67, 68]. In this study, a minimum trench is considered as the pipe outside diameter times 1.25, plus 300 mm, for granular compacted fill to ensure sufficient working space for the compaction equipment used in the pipe zone as per ASTM D2321 [68]. In this study the minimum trench considered for CLSM backfill is the pipe outside diameter times 1.25 as CLSM does not need any compaction in layers as in the case of compacted fill based on the PPI guidelines [67].

In this study, a minimum bedding thickness of 100 mm is considered for a 600 mm diameter pipe and a minimum of 15 cm thickness is considered for the initial backfill layer [68]. The final backfill layer thickness is taken as 1000 mm while referring to the minimum depth of fill as stated on AASHTO HL93 for nominal pipe diameter 60 to 90 cm, which is 91cm [67, 68, 107]. Trench cross section details considered for LCA and LCC for three types of trenches are shown in **Figure 5.2** .



a) Eco-friendly CLSM b) Conventional CLSM c) Granular compacted backfill

Figure 5.2 Trench cross-section details

5.3. Life Cycle Assessment (LCA)

LCA is a methodology to assess the environmental impacts of each process involved in the life cycle of a product or service from a systems perspective as defined in the International Organization for Standardization (ISO) 14040 and 14044 standards [108-111]. In the present study, six impact categories indicators were analyzed, including global warming in kg CO_2 equivalents, mineral resources scarcity in kg Cu equivalents, fossil resources scarcity in kg oil equivalents, ozone formation in kg NOx equivalents, fine particulate matter formation in kg PM equivalents and terrestrial acidification in kg SO_2 equivalents [112].

The following sections describe the methods utilized in the LCA, including the definition of goal and scope, the life cycle inventory, the life cycle impact assessment, and interpretation.

5.3.1. Goal and Scope Definition

a) Purpose of the study

The goal of this LCA was to assess and compare the environmental impacts of three types of backfilling materials used for the utilities trench buried pipe backfilling. The scope of the proposed study system consisted of evaluating the comparison between the six potential environmental impact categories of the mixture proportions that make up the three types of backfilling materials. In addition to this goal, the specific objectives are as follows:

- To determine the contributions of the environmental impact during extraction, transportation, production, and installation phases for each backfill materials,
- To elaborate an inventory of the materials, machinery, and energy consumption in the extraction, transport, production, and installation phases of the life cycle for each backfill material**,**
- To determine the phases and processes contributing the most to the environmental impacts for each backfill material.

b) System boundary

The system boundary for the analysis encompasses the cradle-to-gate approach, with the quarry site serving as the cradle and the installation of backfill material as the gate for the study. The service life and end of life of the filled material are outside the scope of the present study and are not considered in LCA.

The system boundaries for the eco-friendly CLSM (**Figure 5.3**), conventional CLSM (**Figure 5.4**) and granular compacted material (**Figure 5.5**), flowchart consists of four stages from extraction and production of raw materials, transportation of raw materials to the plant, production, which is the mixing of the raw materials at plant and finally installation which incorporates transportation of the materials to site, placing on the site, excavation of soil, loading, cart away, and disposal in landfill. The granular compacted backfill production phase is excluded, as material is delivered to the project site, followed by compaction and backfilling in layers.

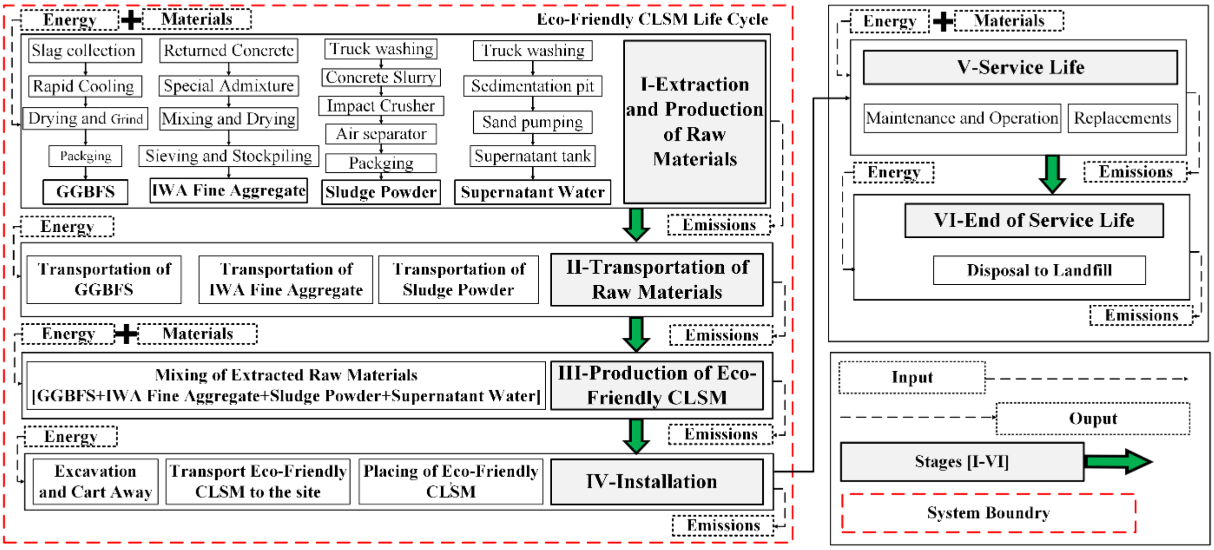


Figure 5.3 System boundary of the scenarios considered for eco-friendly CLSM

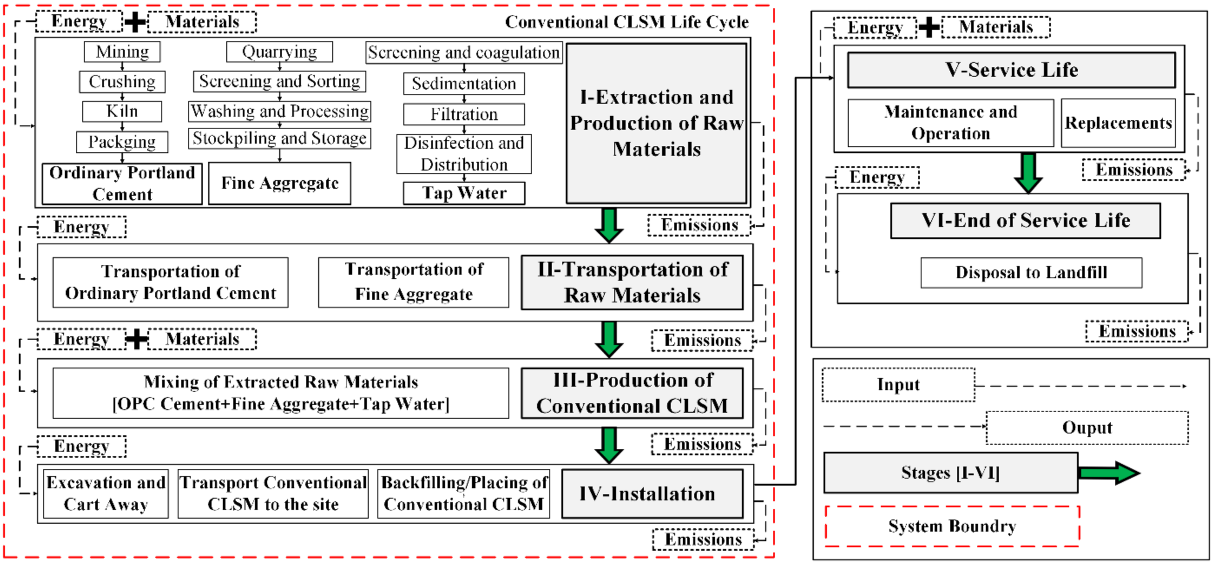


Figure 5.4 System boundary of the scenarios considered for conventional CLSM

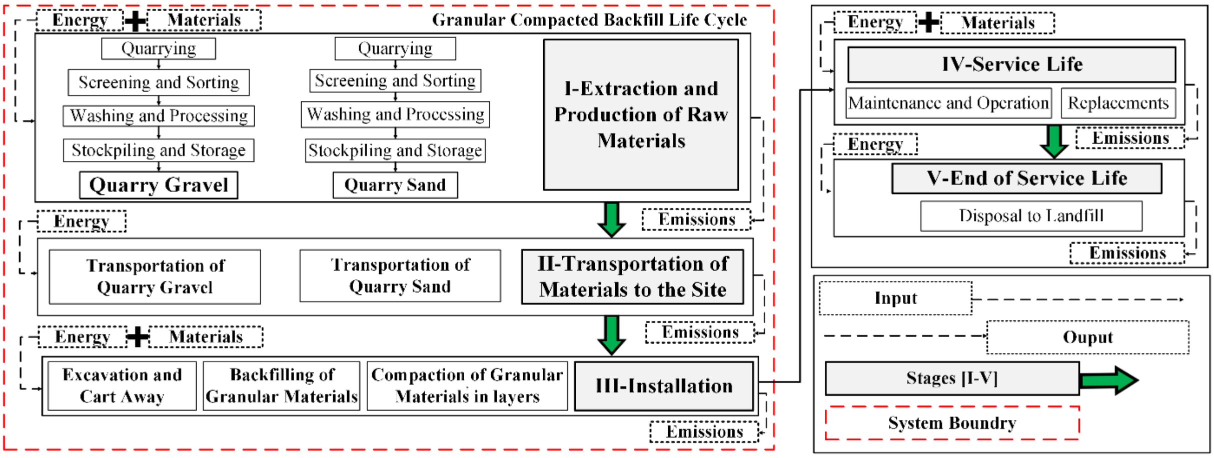


Figure 5.5 System boundary of the scenarios considered for granular compacted backfill

c) Functional unit

In LCA studies, it is necessary to define a functional unit (FU), which serves as the reference unit used to quantify the performance of the product system. In a previous study involving CLSM, 1 ton of CLSM is considered as the FU for the analysis [100]. However, it is common practice to define the FU of systems involving pipes in unit pipeline length [90, 113, 114]. Thus, the FU for this study is one linear meter of trench to install a pipe with a diameter of 600 mm. **Table 5.5**, presents the parameters, options, and their practical implications considered in the inventory tool for utilities trench backfilling.

Table 5.5 Parameters, options, and their description are considered in the study

Parameter	Options	Description
Location	Urban	Urban area is assumed at one site backfilled by Nagaoka RMC
	Non-Urban	
Pipe material	PVC	Pipe material characteristics excluded from LCA
	HDPE	
	Reinforced concrete	
Pipe diameter	Ø 200 mm to Ø 2500 mm	Pipe Ø600 mm were selected to provide detailed comparison of results related to LCA
Type of soil	Soft	Diesel consumption during excavation depends on the type of soil. Soft soil was assumed excavation with consideration to landfill for disposal. Controlled disposal in an authorized landfill of inert earth waste with a density of 1.6 t/m^3. Soil volume conversion factor for soft soil 1.25 is considered.
	Compact	
	Rocky	
Transport distances	Case specific	Transport distances between the manufacturing factory, concrete plant, and project site can be defined for each material.
Pavement	Flexible Pavement	The road is assumed to be paved but excluded from LCA
	Rigid Pavement	
Landfill site	Cart away	Leachate-controlled type is considered for excavated soils disposal

In this study location and actual transport distance between material source, concrete plant, and project site are considered from google map. Nagaoka RMC company located at Shizuoka prefecture is considered as RMC plant, and one of the site which backfilled by the company in Numazu city is selected as the project site, and for landfilling site in recycling center at Izunokuni city considered and granular materials such as gravel and sand are supplied to company from Yamanashi prefecture, and OPC from the Taiheiyo Cement Corporation and GGBFS from Nippon Steel and finally for in situ materials such as IWA fine aggregate, CSP and also for mixing water such as supernatant water and tap water are considered as zero. **Table 5.6** summarizes the data sources used for location and actual transport distance between material source, concrete plant, and project site.

Table 5.6 Location and actual transport distance between source, plant, and project site

Items	Entity	Origin	Destination	Distance (km)
OPC	Taiheiyo Cement Fujiwara Plant	Inabe City, Mie Prefecture	Izunokuni City, Shizuoka Prefecture	284
GGBFS	Nippon Steel Kimitsu Area	Kimitsu City, Chiba Prefecture	Izunokuni City, Shizuoka Prefecture	178
Fine aggregate	Ishimori Industry Co., Ltd.	Nanbu Town, Yamanashi Prefecture	Izunokuni City, Shizuoka Prefecture	73
IWA fine aggregate	Nagaoka Ready-Mixed Concrete	Izunokuni City, Shizuoka Prefecture	Izunokuni City, Shizuoka Prefecture	Recycled in situ*
CSP	Nagaoka Ready-Mixed Concrete	Izunokuni City, Shizuoka Prefecture	Izunokuni City, Shizuoka Prefecture	Recycled in situ*
Gravel	Ishimori Industry Co., Ltd.	Nanbu Town, Yamanashi Prefecture	Numazu City, Shizuoka Prefecture	51
Sand	Ishimori Industry Co., Ltd.	Nanbu Town, Yamanashi Prefecture	Numazu City, Shizuoka Prefecture	51
Landfilling	Kimura Doboku Co., Ltd.	Izunokuni City, Shizuoka Prefecture	Izunokuni City, Shizuoka	5.4
Project site	Nagaoka Ready-Mixed Concrete	Numazu City, Shizuoka Prefecture	Numazu City, Shizuoka Prefecture	9.7

* *Material recycled at the RMC batching plant is considered 0 km.*

5.3.2. Life Cycle Inventory (LCI)

Life cycle Inventory (LCI) analysis (ISO 14041) [109] has to do with compiling input and output inventory data that is not only consistent with the product being assessed but also involves several environmental areas. The LCI process involves developing an inventory containing data corresponding to the input and output flows for the product system. In this study, data for the inventory was collected from local construction companies, construction databases and from previous study inventory data [102, 103, 115]. Emission inventory data necessary for the evaluation of environmental impact related to the processes involved with materials, energy and transport was used from previous comprehensive study by Kawai et al.

on inventory data and case studies for environmental performance evaluation of concrete structure construction [102, 103]. The public database BEDEC, developed by the Construction Technology Institute of Catalonia (ITeC), was also used to obtain detailed information on the processes and materials, as well as the type of machinery for the installation and its consumption obtained from this source [115]. Based on the dimensions modelled in each trench design, we created the LCI using the unitary processes included in the BEDEC database, which include material amounts and composition, energy consumption of construction equipment and rate output for labor and equipment. Types of machinery considered, and their respective emission inventory data are presented in **Table 5.7**. Details of all inventory data utilized in this study are presented in **Appendix B**.

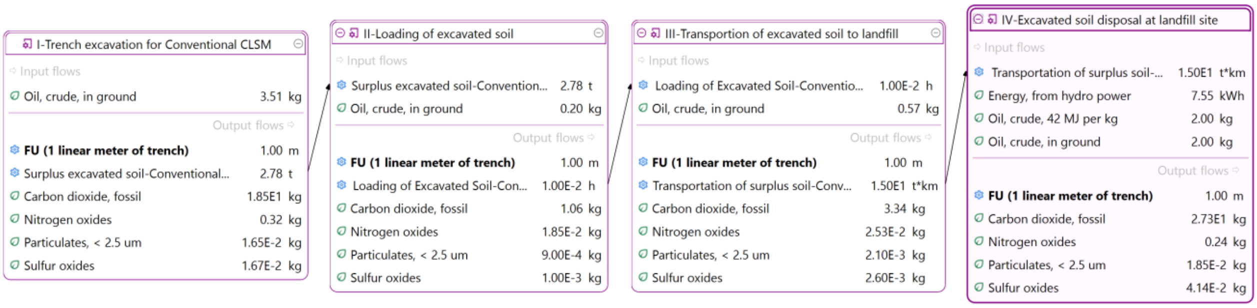
Table 5.7 Types of equipment considered and their respective emission inventory data

Types of Equipment	Unit (*)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Truck diesel (20t)	km.t	0.0714	0.0000549	0.000534	0.0000448
Dump truck diesel (10t)	km.t	0.106	0.0000836	0.000811	0.0000681
Agitator truck (0.8-0.9m^3)	km.t	0.378	0.000297	0.00288	0.000242
Backhoe excavator (0.6m^3)	h	51.7	0.0398	0.774	0.0393
Concrete mixer (1.5m^3)	m^3	0.73	0.000235	0.000289	0.0000542
Agitator truck (0.8-0.9m^3)	h	10.0	0.00769	0.0747	0.00628
Vibrating tamper (60-100kg)	h	2.1	0.000000451	0.0000132	0.000000489

5.3.3. Life Cycle Impact Assessment (LCIA)

A life cycle impact assessment (LCIA) as per ISO 14042 is a multiple-issue tool that is used to evaluate potential environmental impacts that are in line with the environmental resources (inputs and outputs) identified in the life cycle inventory [110]. The LCIA stage is the step where the impacts are evaluated based on the LCI data. The environmental impacts of each design were obtained at the life cycle impact assessment stage. It was performed using the OpenLCA 2.4.1 software through the classification and characterization steps defined by ISO (2006). To perform LCA studies, a variety of LCIA methods are available. The International Standard for LCA (ISO 14040-14044) [109-111]does not specify which LCIA method should be used, which means the choice of LCIA method differs per study. In this study, the ReCiPe (H) method [112], which provides a state-of-the-art method to convert life cycle inventories to life cycle impact scores at the midpoint and endpoint levels, with a focus on providing characterization factors that are representative on a global scale, in line with the global nature of many product life cycles, was applied.

The model graph in openLCA represents a product system, illustrating the flow of materials and energy between various processes. The model graph for conventional CLSM stages is presented in **Figure 5.6** and **Figure 5.7**, respectively.



I-Trench excavation for Conventional CLSM

Input flows		
Oil, crude, in ground	3.51	kg
Output flows		
FU (1 linear meter of trench)	1.00	m
Surplus excavated soil-Conventional...	2.78	t
Carbon dioxide, fossil	1.85E1	kg
Nitrogen oxides	0.32	kg
Particulates, < 2.5 um	1.65E-2	kg
Sulfur oxides	1.67E-2	kg

II-Loading of excavated soil

Input flows		
Surplus excavated soil-Convention...	2.78	t
Oil, crude, in ground	0.20	kg
Output flows		
FU (1 linear meter of trench)	1.00	m
Loading of Excavated Soil-Con...	1.00E-2	h
Carbon dioxide, fossil	1.06	kg
Nitrogen oxides	1.85E-2	kg
Particulates, < 2.5 um	9.00E-4	kg
Sulfur oxides	1.00E-3	kg

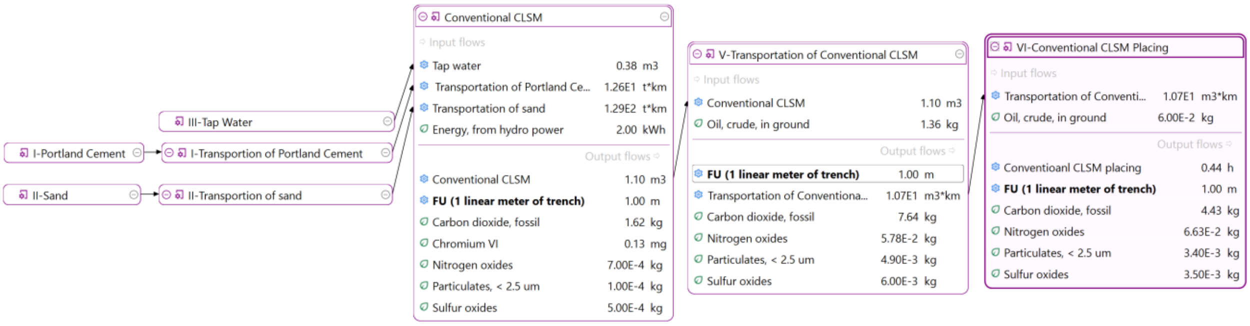
III-Transportion of excavated soil to landfill

Input flows		
Loading of Excavated Soil-Conventio...	1.00E-2	h
Oil, crude, in ground	0.57	kg
Output flows		
FU (1 linear meter of trench)	1.00	m
Transportation of surplus soil-Conv...	1.50E1	t*km
Carbon dioxide, fossil	3.34	kg
Nitrogen oxides	2.53E-2	kg
Particulates, < 2.5 um	2.10E-3	kg
Sulfur oxides	2.60E-3	kg

IV-Excavated soil disposal at landfill site

Input flows		
Transportation of surplus soil-...	1.50E1	t*km
Energy, from hydro power	7.55	kWh
Oil, crude, 42 MJ per kg	2.00	kg
Oil, crude, in ground	2.00	kg
Output flows		
FU (1 linear meter of trench)	1.00	m
Carbon dioxide, fossil	2.73E1	kg
Nitrogen oxides	0.24	kg
Particulates, < 2.5 um	1.85E-2	kg
Sulfur oxides	4.14E-2	kg

Figure 5.6 The model graph for the excavation stage of conventional CLSM



Conventional CLSM

Input flows		
Tap water	0.38	m3
Transportation of Portland Ce...	1.26E1	t*km
Transportation of sand	1.29E2	t*km
Energy, from hydro power	2.00	kWh
Output flows		
Conventional CLSM	1.10	m3
FU (1 linear meter of trench)	1.00	m
Carbon dioxide, fossil	1.62	kg
Chromium VI	0.13	mg
Nitrogen oxides	7.00E-4	kg
Particulates, < 2.5 um	1.00E-4	kg
Sulfur oxides	5.00E-4	kg

V-Transportation of Conventional CLSM

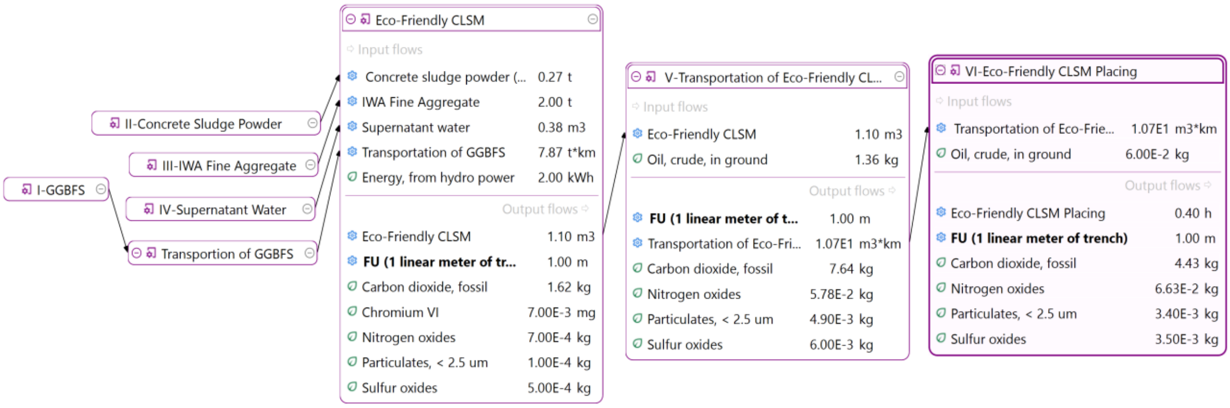
Input flows		
Conventional CLSM	1.10	m3
Oil, crude, in ground	1.36	kg
Output flows		
FU (1 linear meter of trench)	1.00	m
Transportation of Conventiona...	1.07E1	m3*km
Carbon dioxide, fossil	7.64	kg
Nitrogen oxides	5.78E-2	kg
Particulates, < 2.5 um	4.90E-3	kg
Sulfur oxides	6.00E-3	kg

VI-Conventional CLSM Placing

Input flows		
Transportation of Conventi...	1.07E1	m3*km
Oil, crude, in ground	6.00E-2	kg
Output flows		
Conventioanl CLSM placing	0.44	h
FU (1 linear meter of trench)	1.00	m
Carbon dioxide, fossil	4.43	kg
Nitrogen oxides	6.63E-2	kg
Particulates, < 2.5 um	3.40E-3	kg
Sulfur oxides	3.50E-3	kg

Figure 5.7 The model graph for the extraction to installation stages of conventional CLSM

The model graph of excavation for eco-friendly CLSM is the same as that of conventional CLSM, as presented in **Figure 5.6**. The model graph for eco-friendly CLSM from the extraction to installation stages is presented in **Figure 5.8**.



Eco-Friendly CLSM

Input flows	
Concrete sludge powder (...	0.27 t
IWA Fine Aggregate	2.00 t
Supernatant water	0.38 m3
Transportation of GGBFS	7.87 t*km
Energy, from hydro power	2.00 kWh
Output flows	
Eco-Friendly CLSM	1.10 m3
FU (1 linear meter of tr...	1.00 m
Carbon dioxide, fossil	1.62 kg
Chromium VI	7.00E-3 mg
Nitrogen oxides	7.00E-4 kg
Particulates, < 2.5 um	1.00E-4 kg
Sulfur oxides	5.00E-4 kg

V-Transportation of Eco-Friendly CL...

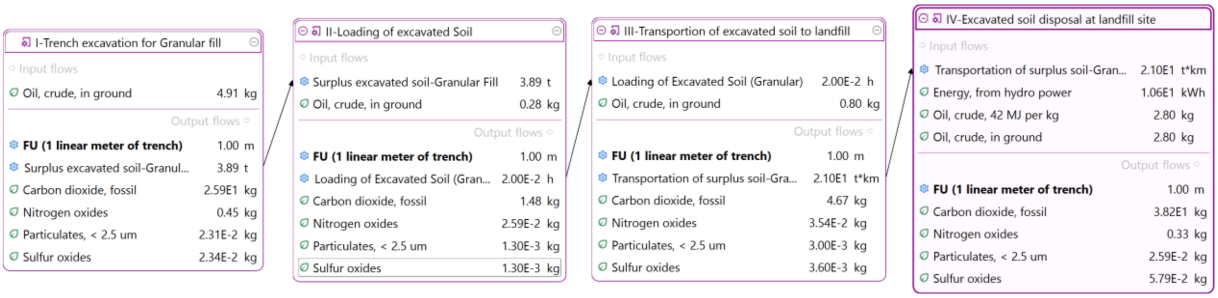
Input flows	
Eco-Friendly CLSM	1.10 m3
Oil, crude, in ground	1.36 kg
Output flows	
FU (1 linear meter of t...	1.00 m
Transportation of Eco-Fri...	1.07E1 m3*km
Carbon dioxide, fossil	7.64 kg
Nitrogen oxides	5.78E-2 kg
Particulates, < 2.5 um	4.90E-3 kg
Sulfur oxides	6.00E-3 kg

VI-Eco-Friendly CLSM Placing

Input flows	
Transportation of Eco-Frie...	1.07E1 m3*km
Oil, crude, in ground	6.00E-2 kg
Output flows	
Eco-Friendly CLSM Placing	0.40 h
FU (1 linear meter of trench)	1.00 m
Carbon dioxide, fossil	4.43 kg
Nitrogen oxides	6.63E-2 kg
Particulates, < 2.5 um	3.40E-3 kg
Sulfur oxides	3.50E-3 kg

Figure 5.8 The model graph for the extraction to installation stages of eco-friendly CLSM

The model graph for the excavation stage and onsite installation for granular compacted fill is presented in **Figure 5.9** and **Figure 5.10**, respectively.



I-Trench excavation for Granular fill

Input flows	
Oil, crude, in ground	4.91 kg
Output flows	
FU (1 linear meter of trench)	1.00 m
Surplus excavated soil-Granul...	3.89 t
Carbon dioxide, fossil	2.59E1 kg
Nitrogen oxides	0.45 kg
Particulates, < 2.5 um	2.31E-2 kg
Sulfur oxides	2.34E-2 kg

II-Loading of excavated Soil

Input flows	
Surplus excavated soil-Granular Fill	3.89 t
Oil, crude, in ground	0.28 kg
Output flows	
FU (1 linear meter of trench)	1.00 m
Loading of Excavated Soil (Gran...	2.00E-2 h
Carbon dioxide, fossil	1.48 kg
Nitrogen oxides	2.59E-2 kg
Particulates, < 2.5 um	1.30E-3 kg
Sulfur oxides	1.30E-3 kg

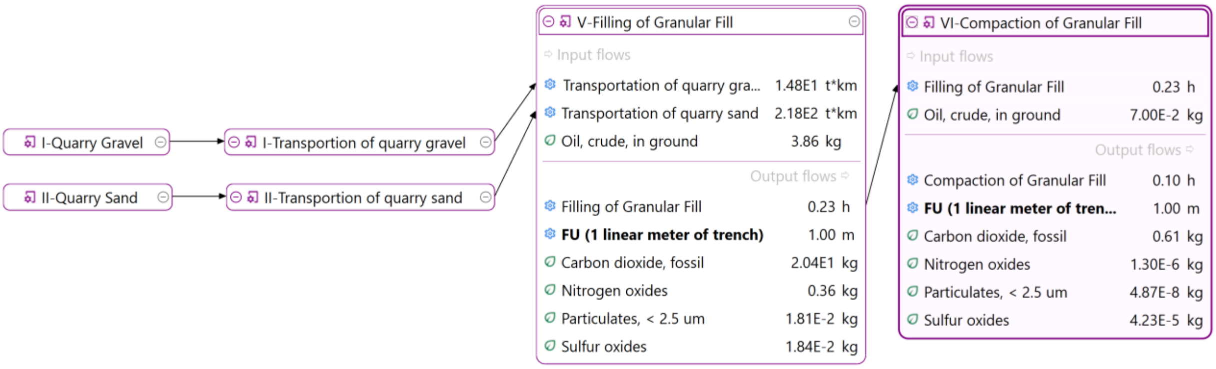
III-Transportion of excavated soil to landfill

Input flows	
Loading of Excavated Soil (Granular)	2.00E-2 h
Oil, crude, in ground	0.80 kg
Output flows	
FU (1 linear meter of trench)	1.00 m
Transportation of surplus soil-Gra...	2.10E1 t*km
Carbon dioxide, fossil	4.67 kg
Nitrogen oxides	3.54E-2 kg
Particulates, < 2.5 um	3.00E-3 kg
Sulfur oxides	3.60E-3 kg

IV-Excavated soil disposal at landfill site

Input flows	
Transportation of surplus soil-Gran...	2.10E1 t*km
Energy, from hydro power	1.06E1 kWh
Oil, crude, 42 MJ per kg	2.80 kg
Oil, crude, in ground	2.80 kg
Output flows	
FU (1 linear meter of trench)	1.00 m
Carbon dioxide, fossil	3.82E1 kg
Nitrogen oxides	0.33 kg
Particulates, < 2.5 um	2.59E-2 kg
Sulfur oxides	5.79E-2 kg

Figure 5.9 The model graph for the excavation stage of granular compacted fill



V-Filling of Granular Fill

Input flows	
Transportation of quarry gra...	1.48E1 t*km
Transportation of quarry sand	2.18E2 t*km
Oil, crude, in ground	3.86 kg
Output flows	
Filling of Granular Fill	0.23 h
FU (1 linear meter of trench)	1.00 m
Carbon dioxide, fossil	2.04E1 kg
Nitrogen oxides	0.36 kg
Particulates, < 2.5 um	1.81E-2 kg
Sulfur oxides	1.84E-2 kg

VI-Compaction of Granular Fill

Input flows	
Filling of Granular Fill	0.23 h
Oil, crude, in ground	7.00E-2 kg
Output flows	
Compaction of Granular Fill	0.10 h
FU (1 linear meter of tren...	1.00 m
Carbon dioxide, fossil	0.61 kg
Nitrogen oxides	1.30E-6 kg
Particulates, < 2.5 um	4.87E-8 kg
Sulfur oxides	4.23E-5 kg

Figure 5.10 The model graph for the extraction to installation stages of compacted fill

5.3.4. Interpretation

Interpretation, which is the last stage, is an efficient method used to evaluate, compute, and categories the results from the information provided by the LCI and the LCIA, and to relate them effectively [111]. In the last step of the LCA, based on the information from the results of the LCI and the LCIA are evaluated, and conclusions are extracted. In this study, the interpretation of the results was performed primarily using the results of four stages in LCA. Results from the LCA of all three materials analyses were used to understand to what extent each stage and materials may influence the outcomes from the LCA, and the conclusions drawn.

5.4. Life Cycle Costing (LCC)

Life cycle costing, also known as whole-life costing, involves estimating the total expenses associated with an asset over its useful lifespan [116]. In this analysis, costs are reported from the extraction stage to the on-site placement of the material, excluding the assessment of service life and end-of-life disposal costs. The construction cost comprises both direct and indirect expenses. The total estimated direct cost represents the accumulation of direct costs for each required pay item, as depicted in the design drawings and specified in the technical specification [117]. In this study, direct cost survey forms were developed, and direct cost information was obtained from the RMC producer.

The cost comparison between eco-friendly CLSM, conventional CLSM and conventional backfill (sand and gravel) was performed as per mix design and trench cross section details of each material within functional unit of 1m trench. The factors used in the cost analyses were labor (including fringe benefits), equipment (including fuel, lubricants, maintenance), and materials (including handling). The cost of CLSM per cubic meter was calculated based on the cost of materials and the cost of labor and equipment cost. The cost of transporting the material to the site and placing it at site was included in the price per cubic meter. The amount of material used was determined by using the volume of the trench, minus pipe volume. The equipment cost was based on an hourly rate that was derived from the cost of monthly rental.

In the excavation stage of cost analysis was calculated based on detail trench cross-section details. When using compacted granular backfill, there is working space needed in the trench because laborers have to be in the trench to compact the backfill material. However, the volume of a trench where flowable fill is used is significantly less than the volume of a trench where conventional backfill is used. The only dimensional change occurs in the width of the trench. This reduction in trench width reduces the total cost of the CLSM backfill. Therefore, with reduced trench width, the CLSM backfill material is at least equivalent in costs to the manufactured sand backfill [27, 118].

5.4.1. Direct Costs (DC)

The direct cost (DC) includes costs due to materials, labor, and equipment, whereas the indirect cost (IC) essentially covers overhead costs and the contractor's profit. The DCs of each pay item are calculated by multiplying the quantity by its unit rate. The quantities of each item shall be obtained based on the design drawings and/or technical specifications. DC for each work item shall be calculated as the combination of basic labor cost, material cost, and equipment cost based on the productivity of the work in relation to the construction method and procedure [119]. Details of all direct cost analysis in this study are presented in **Appendix C**.

5.4.2. Indirect Costs (IC)

Indirect cost (IC) consists of OCM (overhead, contingencies, and miscellaneous) and profits[120]. Overhead costs are expenses for general office facilities, rents, taxes, electricity light, water, and other miscellaneous items [121]The value added tax (VAT) shall be applied to the total of the direct and indirect costs. In this study, IC analysis and VAT were not included in the LCC comparisons for three backfilling materials.

5.4.3. Rate Analysis for Direct Cost

Rate analysis is the process of fixing cost per unit of measurement for the different items of work [117]. Total cost per unit of work (TC) may be grouped into two components: DC and IC [122]. In order to facilitate estimation of cost due to material, it is important to know the quantities of various materials involved in construction of various parts of the building or construction work i.e. material breakdown is essential. In this study rate analysis consists of material cost breakdown is prepared and calculated.

The cost analysis is conducted in four stages, namely excavation, carting away, filling, and compaction. During the excavation stage of a utility trench, items considered include mechanical excavation, carting away, which involves loading the excavated surplus soil into a dump truck, transporting it to the landfill site, and disposing of it in a leachate-controlled manner at the landfill site. In the filling stage, the cost of each backfilling material is broken down and analysed, including transportation to the site and placement or filling at the site. The cost determination method provided should help establish a realistic and competitive price for all backfilling materials. The direct cost of backfilling material per cubic meter was calculated using rate analysis, and then the total price is calculated based on the quantity required per meter of trench, FU assumed [118].

a) Labor Cost

Basic labor cost used for the life cycle cost analysis estimated based on the unit price for public works design and labor prepared by the Research Institute on Building Cost (RIBC) of Ministry of Land, Infrastructure, Transport and Tourism market assessment for the current year (2025) labor unit price were utilized [123]. The construction work is planned to be carried out in the daytime of eight working hours per day so that extra overtime for the night work was not considered. The list of labor included in the rate analysis was site supervisor, considering the utilization factor of half as he may be committed to controlling other tasks alongside backfilling activities, equipment operator, driver, and daily labor.

b) Material Cost

The material cost information used to calculate the life cycle cost of backfilling materials was estimated based on a local market survey and the costs used in other projects by the RMC company. The material costs include the purchasing cost, loading and unloading cost, and transportation from the origin to the plant or site.

c) Equipment Cost

The operating hour rental rates include the cost of fuel, lubricants, and maintenance, excluding the cost of the driver or equipment operator [118]. The operated equipment rental contract can be either a day-to-day contract or a month-to-month contract. In this study, the monthly rental costs for the operated equipment, obtained from the RMC company, were converted to an hourly operating cost, taking into account the working days and daily operating hours.

5.5. Summary

This chapter presented a detailed description and methodology of life cycle assessment methods, including goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation. Additionally, life cycle costing analysis methodology, including rate analysis of direct costs such as materials, labor, and equipment, is explained. The comprehensive life cycle assessment and life cycle costing analysis ensure the reliability and validity of the results, which will be discussed in the subsequent chapter.

CHAPTER 6: LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING RESULT AND DISCUSSION

6.1. Introduction

This chapter presents the life cycle assessment (LCA) analysis findings comparing three backfilling materials, and characterizes the potential impacts on global warming, mineral resource depletion, fossil fuel exhaustion, ozone layer formation, terrestrial acidification, and the formation of fine particulate matter. Furthermore, the life cycle cost (LCC) comparative analysis results from the direct cost analysis are also included. The findings are presented below in graphical and tabular formats.

6.2. Life Cycle Assessment Result

6.2.1. Global Warming

Global warming refers to the climatic effect of increased human-driven emissions of large amounts of greenhouse gases, particularly from the burning of fossil fuels and large-scale deforestation, with carbon dioxide being the most significant contributor [124]. Eco-friendly CLSM demonstrates a uniquely low net warming impact (19.9 kg CO_2 eq). Although its installation phase emits 62.3 kg CO_2 eq (312.72% of its own total), the CSP incorporated during

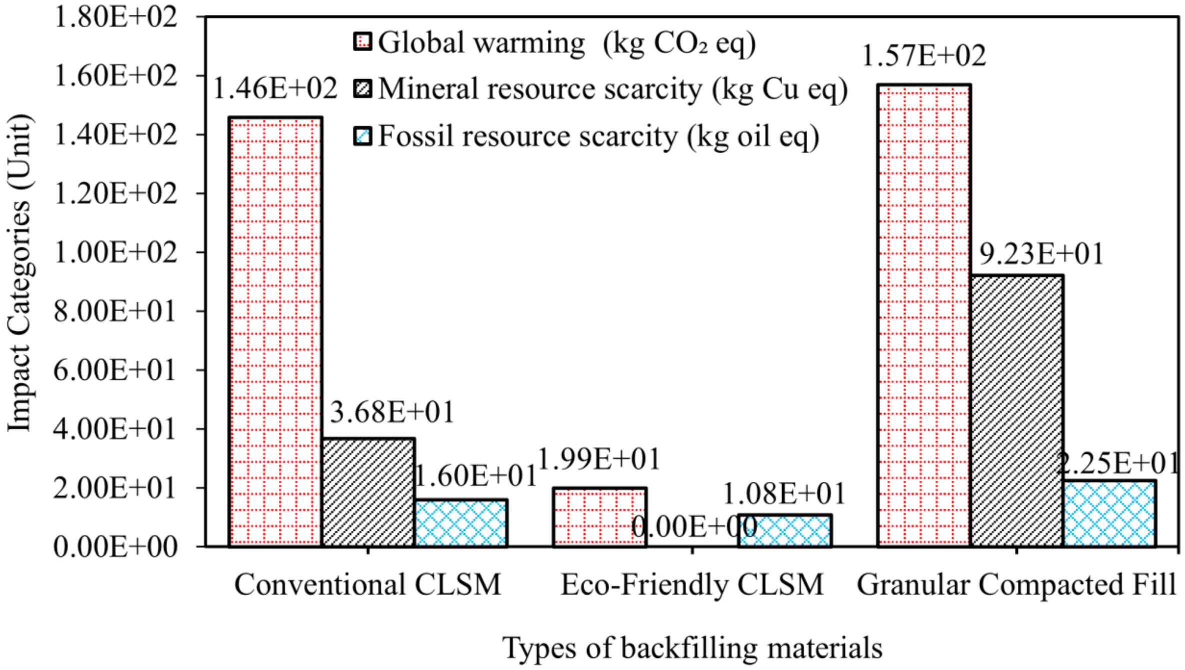


Figure 6.1 Comparison of global warming, mineral, and fossil resource scarcity

extraction sequesters 45.1 kg CO_2 eq (–226.48%), yielding a strong carbon sink and driving the life cycle balance toward a minimal footprint, as depicted in **Figure 6.1** and **Table 6.1** respectively [104]. Conventional CLSM emits a total of 146 kg CO_2 eq, split almost equally between extraction (61.7 kg, 42.32 %) and installation (62.3 kg, 42.69 %), with transport (20.2 kg, 13.87 %) and production (1.62 kg, 1.11 %) making smaller contributions, as shown in **Figure 6.1**. Granular compacted fill bears the most significant warming burden (157 kg CO_2 eq), dominated by installation (91.2 kg, 58.15%), followed by transport (33.2 kg, 21.18%) and extraction (32.4 kg, 20.67%), as illustrated in **Figure 6.1**.

Table 6.1 provides a comparative analysis of the LCA results, showcasing the percentage contributions of the different stages, encompassing raw material extraction, transportation, production, and installation, across global warming, fossil resource scarcity and mineral resource scarcity impact categories for the three backfilling materials.

Table 6.1 Stages contribution in global warming, fossil and mineral resource scarcity

Type of Material	Stages	Global warming (kg CO_2 eq)	Fossil resource scarcity (kg oil eq)	Mineral resource scarcity (kg Cu eq)
Conventional CLSM	Extraction	42.32%	19.46%	100%
	Transportation	13.87%	20.44%	-
	Production	1.11%	-	-
	Installation	42.69%	60.10%	-
Eco-Friendly CLSM	Extraction	-226.48%	9.32%	-
	Transportation	5.63%	1.66%	-
	Production	8.14%	-	-
	Installation	312.72%	89.02%	-
Granular Compacted Fill	Extraction	20.67%	7.51%	100%
	Transportation	21.18%	23.90%	-
	Production	-	-	-
	Installation	58.15%	68.59%	-

Compared to conventional CLSM and granular compacted fill, eco-friendly CLSM demonstrates a significantly lower global warming impact, with a net emission of just 19.9 kg

CO_2-equivalent per cubic meter. This reduction is attributed to its unique ability to balance CO_2 uptake during raw material extraction with emissions generated during installation [98, 125, 126]. In contrast, granular compacted fill exhibits the highest environmental burden, reaching 157 kg CO_2-equivalent per cubic meter. Notably, across all three materials, the installation phase remains the dominant contributor to overall global warming impacts. In the development of eco-friendly CLSM, the use of concrete sludge powder, IWA fine aggregate, and supernatant water plays a crucial role in minimizing emissions [126]. Concrete sludge powder actively captures CO_2, and significantly cut down the embodied carbon emissions, making eco-friendly CLSM a far more sustainable alternative [104].

6.2.2. Mineral Resource Scarcity

Eco-friendly CLSM eliminates primary mineral resources depletion by substituting fully recycled RC waste for virgin aggregates and industrial by-products for OPC binder [47]. This yields zero mineral-scarcity impacts across extraction, transport, production, and installation. In conventional CLSM, depletion of virgin minerals totals 36.8 kg Cu eq from extraction alone **(Figure 6.1**). Granular compacted fill similarly consumes 92.3 kg Cu eq at extraction (100 %), with negligible impacts in later stages, as depicted in **Figure 6.1.** In eco-friendly CLSM development, replacing the use of virgin materials with GGBFS, CSP, IWA fine aggregate, and supernatant water avoids the extraction of new raw materials, thereby eliminating the impacts of mineral scarcity. The consumption of natural minerals strongly influences the origin of these values, though materials such as quartz and limestone, are globally abundant, there may be local scarcity, considered by this indicator in terms of consumption of resources[127]. Notably, across all three materials, the extraction phase remains the dominant contributor to overall mineral resource scarcity impact categories for conventional CLSM and granular compacted material [127].

6.2.3. Fossil Resource Scarcity

In terms of absolute value, this category is the one with the highest value in the installation phases, which dominates fossil-fuel use for each backfill. Eco-friendly CLSM consumes 10.8 kg oil eq (89.02 % of its 10.8 kg total) to installation and placement, with extraction at 1.01 kg (9.32 %) and transport at 0.18 kg (1.66 %), as depicted in **Figure 6.1**. Conventional CLSM consumes 16 kg of oil eq, divided into installation (9.64 kg, 60.1 %), transport (3.28 kg, 20.44 %), and extraction (3.12 kg, 19.46 %), as shown in **Figure 6.1**. Granular fill peaks at 22.5 kg oil eq, split among installations (15.4 kg, 68.59 %), transport (5.38 kg, 23.9 %) and extraction (1.69 kg, 7.51 %), as illustrated in **Figure 6.1**. Notably, across all three materials, the extraction phase remains the dominant contributor to overall mineral resource scarcity impact categories for conventional CLSM and granular compacted material.

6.2.4. Ozone Formation

Ozone-precursor emissions are overwhelmingly driven by installation activity. Eco-friendly CLSM emits 0.731 kg NO_x eq (92.06 % of its 0.794 kg total) from mixing and pumping, with extraction contributing 0.054 kg (6.79 %) and transport 0.008 kg (1.06 %), as depicted in **Figure 6.2**. Conventional CLSM releases 0.731 kg NO_x eq (74.84 % of 0.977 kg total) at installation, 0.094 kg (9.6 %) at extraction and 0.151 kg (15.49 %) in transport, with production negligible (0.0007 kg, 0.07 %), as shown in **Table 6.2**. Granular fill emits the most at 1.21 kg installation (79.43 % of 1.52 kg), plus 0.249 kg transport (16.35 %) and 0.064 kg extraction (4.22 %). as presented in **Figure 6.2**.

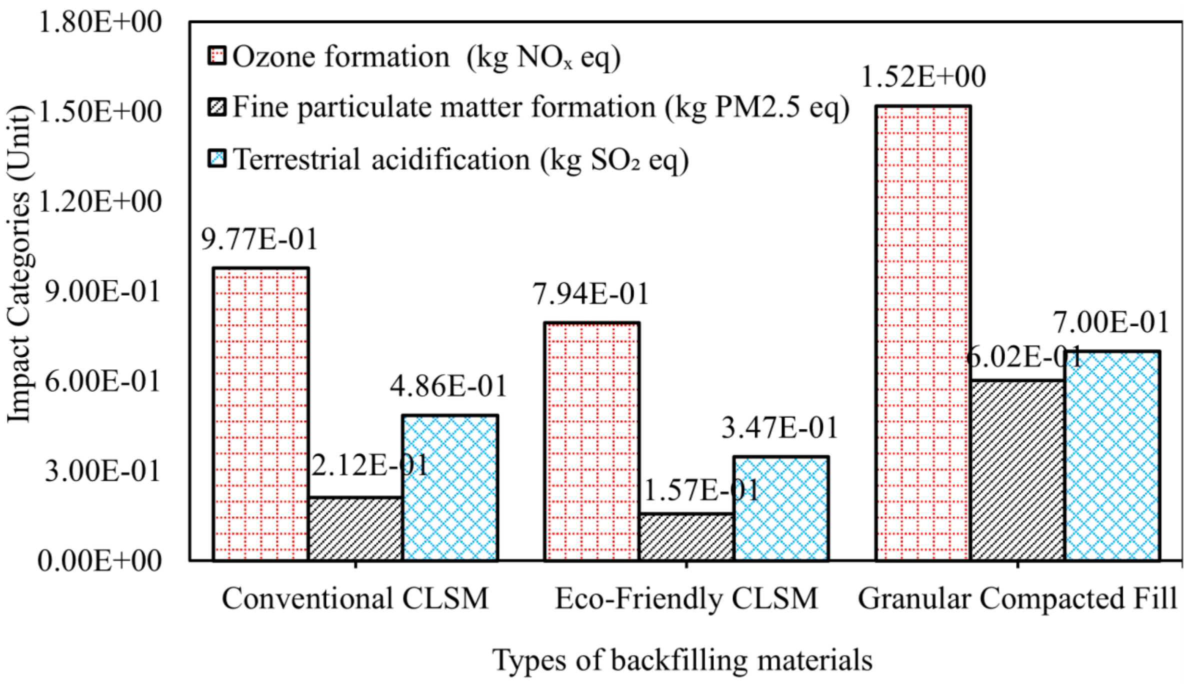


Figure 6.2 Comparison of ozone formation, fine PM2.5 and terrestrial acidification

6.2.5. Fine Particulate Matter Formation

$PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) is a severe air pollution problem. Installation again dominates particulate emissions[128]. Eco-friendly CLSM produces 0.143 kg $PM_{2.5}$ eq (91.05 % of 0.157 kg total), with extraction at 0.0118 kg (7.54 %) and transport at 0.0019 kg (1.2 %), as depicted in **Figure 6.2**. Conventional CLSM emits 0.143 kg (67.2 %) in installation, 0.0354 kg (16.68 %) in extraction, 0.0339 kg (15.97 %) in transport, and 0.0003 kg (0.15 %) in production, totaling 0.212 kg $PM_{2.5}$ eq (**Figure 6.2**). Granular fill has highest fine-particle impact (0.602 kg) split into extraction (0.319 kg, 53.0 %), installation (0.228 kg, 37.8 %) and transport (0.0556 kg, 9.2 %), as shown in **Figure 6.2**.

Table 6.2 provides a comparative analysis of the LCA results, showcasing the percentage contributions of the different stages, encompassing raw material extraction, transportation, production, and installation, across ozone formation, fine particulate formation and terrestrial acidification impact categories impact categories for the three backfilling materials.

Table 6.2 Stages contribution in ozone formation, fine PM2.5 and terrestrial acidification

Type of Material	Stages	Ozone formation (kg NO_x eq)	Fine particulate matter formation (kg PM2.5 eq)	Terrestrial acidification (kg SO_2 eq)
Conventional CLSM	Extraction	9.60%	16.68%	20.10%
	Transportation	15.49%	15.97%	14.41%
	Production	0.07%	0.15%	0.15%
	Installation	74.84%	67.20%	65.33%
Eco-Friendly CLSM	Extraction	6.79%	7.54%	7.17%
	Transportation	1.06%	1.20%	1.13%
	Production	0.09%	0.21%	0.22%
	Installation	92.06%	91.05%	91.48%
Granular Compacted Fill	Extraction	4.22%	52.96%	9.82%
	Transportation	16.35%	9.22%	16.45%
	Production	-	-	-
	Installation	79.43%	37.81%	73.73%

6.2.6. Terrestrial Acidification

Acidifying emissions across all backfill options are primarily driven by the installation phase, which is characterized by fuel combustion in placement equipment and soil disturbance. Eco-friendly CLSM emits a total of 0.808 kg SO_2 eq per m^3: 0.731 kg (90.6 %) during installation, 0.060 kg (7.4 %) in extraction, 0.015 kg (1.8 %) in transport, and a negligible 0.002 kg (0.2 %) from production (**Figure 6.2**). Conventional CLSM generates 0.683 kg SO_2 eq, split into 0.473 kg (69.3 %) installation, 0.124 kg (18.1 %) extraction, 0.083 kg (12.1 %) transport, and 0.004

kg (0.5 %) production (**Figure 6.2**). Granular compacted fill shows the highest acidification potential at 1.00 kg SO_2 eq, with installation accounting for 0.819 kg (81.9 %), transport 0.127 kg (12.7 %) and extraction 0.053 kg (5.3 %), as shown in **Figure 6.2**.

6.3. Life Cycle Cost Analysis Result

The cost of labor for eco-friendly CLM production and placement was calculated based on one daily laborer, mixer operator, one agitator truck driver and one supervisor. Only one half of the supervisor's cost was used due to significant amounts of his time being devoted to other work. The total material cost, including transportation, loading and unloading, was ¥5,500. The labor cost, including benefits, travel subsidies, and cost of overtime related to targeted output, was ¥1,957.43. The total equipment cost, including fuel, lubricants, and filters, was ¥2,625.17. The unit price of eco-friendly CLSM per cubic meter was ¥10,082.60 (**Figure 6.3**). Finally, the total cost per linear meter of trench is found by multiplying the quantity of CLSM with unit price, which was ¥11,138.82, as shown in **Figure 6.4**. Cost related to compaction stage is considered as null as Eco-friendly CLSM does not require compacting in layers as for granular compacted cause. Accordingly, the unit price at all remaining stages excavation and cart away are calculated and multiplied with quantity within meter of trench. The overall total cost of all four stages of Eco-friendly CLSM was ¥21,964.54 [27].

The cost of labor for conventional CLM production and placement was calculated based on one daily laborer, mixer operator, one agitator truck driver and one supervisor. Only one half of the supervisor's cost was used due to significant amounts of his time being devoted to other work. The total material cost, including transportation, loading and unloading, was ¥11,304.8. The labor cost, including benefits, travel subsidies, and cost of overtime related to targeted output, was ¥1,957.43. The total equipment cost, including fuel, lubricants, and filters, was ¥2,625.17. The unit price of eco-friendly CLSM per cubic meter was ¥15,887.40 (**Figure 6.3**). Finally, the total cost per linear meter of trench is found by multiplying the quantity of CLSM with unit price, which was ¥17,551.71, as illustrated in **Figure 6.4**. The cost related to compaction stage is considered as null as conventional CLSM does not require compacting in layers as for granular compacted cause. Accordingly, the unit price at all remaining stages excavation and cart away are calculated and multiplied with quantity within meter of trench. The overall total cost of all four stages of conventional CLSM was ¥28,377.43.

The conventional backfill material was manufactured sand and gravel. The cost of labor for conventional backfill placement was calculated based on one equipment operator and one supervisor. Only one half of the supervisor's cost was used due to significant amounts of his time being devoted to other work. The total material cost, including transportation, loading and unloading, was ¥17,713. The labor cost, including benefits, travel subsidies, and cost of overtime related to targeted output, was ¥281.27. The total equipment cost, including fuel, lubricants, and filters, was ¥420. The unit price of granular compacted per cubic meter was ¥18,414.27 (**Figure 6.3**). Finally, the total cost per linear meter of trench is found by multiplying the quantity of granular materials with unit price, which was ¥30,563.21, as depicted in **Figure 6.4**. The cost of compaction of granular material was calculated separately in the final stage considering one daily laborer, tamper operator and one supervisor along with one vibrating tamper. Accordingly, the unit price at all remaining stages excavation, cart away and compaction are calculated and multiplied with quantity within meter of trench. The overall total cost of all four stages of granular compacted fill was ¥46,698.98.

The life-cycle cost (LCC) comparison of three backfilling materials, conventional CLSM, eco-friendly CLSM, and granular compacted fill analyses, reveals that the filling stage overwhelmingly dominates total costs in every case. On a per-meter-of-trench basis, Conventional CLSM incurs ¥2,080.08 for excavation stage, ¥8,745.63 for carting away stage,

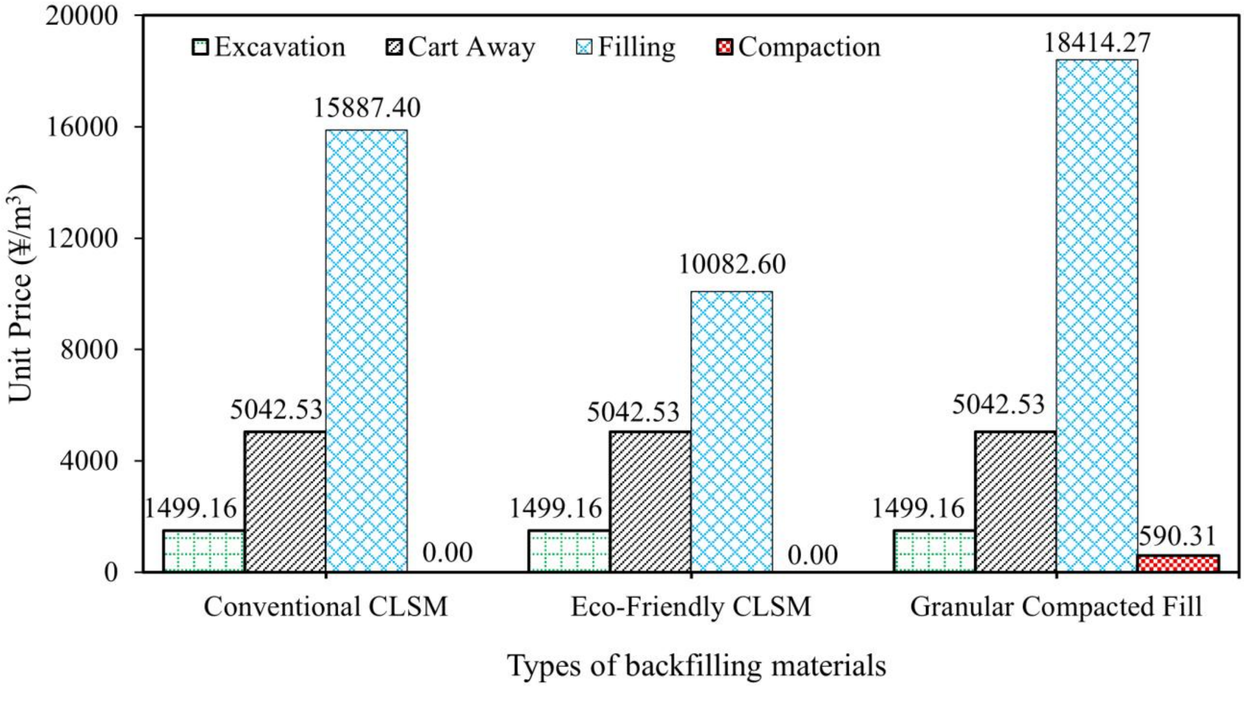


Figure 6.3 Unit price comparison for each stage of the LCC

and ¥17,551.71 for filling stage and null for compaction, totaling ¥28,377.43. as presented in **Figure 6.4** Eco-Friendly CLSM holds excavation and cart-away costs constant at ¥2,080.08 and ¥8,745.63, respectively, but reduces the filling cost to ¥11,138.82 bringing its total to ¥21,964.54, a 22.6% savings over conventional CLSM (**Figure 6.4**). Granular compacted fill rises excavation to ¥2,912.12 and cart-away to ¥12, 243.89, but despite adding a compacting cost of ¥979.77, its filling cost (¥30,563.21) yields a total of ¥46,698.98 (**Figure 6.4**).

On a unit-volume (¥/m³) basis, excavation costs ¥1,499.16 for all three materials, and cart-away costs ¥5,042.53. filling costs differ significantly ¥15,887.40 for conventional CLSM, ¥10,082.60 for eco-friendly CLSM, and ¥18,414.27 for granular compacted fill while compaction is null for the CLSM mixes and ¥590.31 for the granular fill, as presented in **Figure 6.3**. In percentage terms per cubic meter as shown in **Table 6.3**, filling still dominates with 70.83%, 60.65%, and 72.08% of the unit price, respectively, underscoring that material selection and mix design principally influence the filling stage share of the total life-cycle cost.

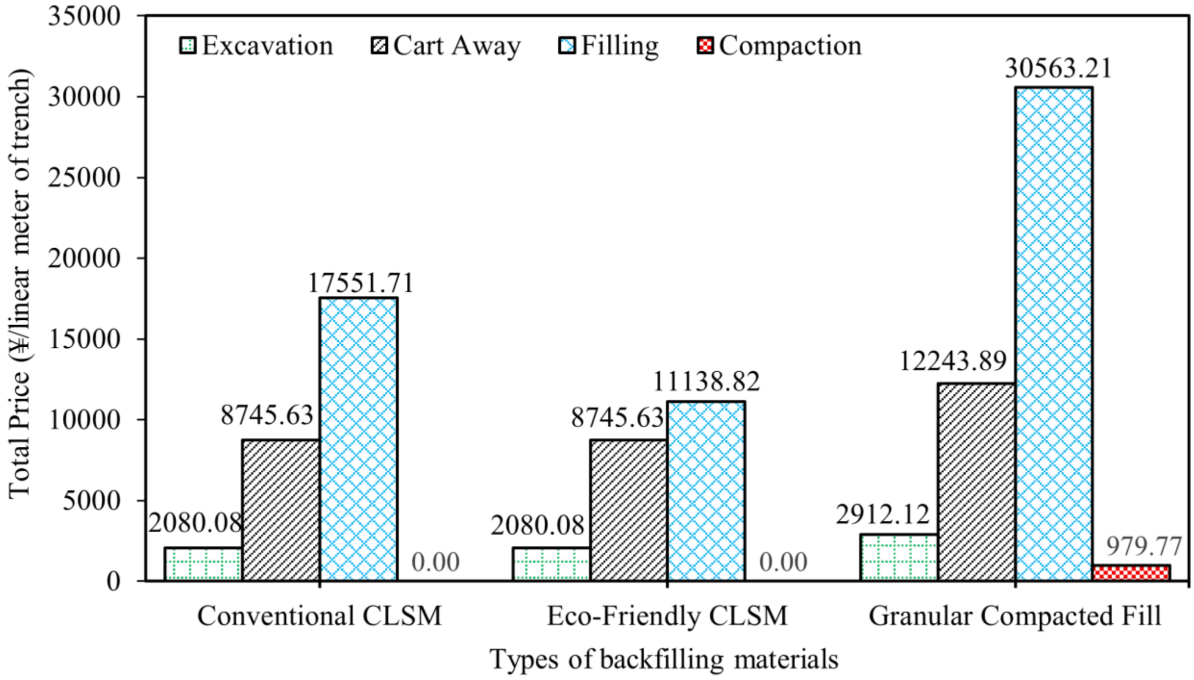


Figure 6.4 Total price comparison for each stage of the LCC

Based on the results presented in **Table 6.3** the contribution of each stage expressed as percentages of total LCC per linear meter indicates that the filling stage accounts for roughly 61.85% in conventional CLSM, 50.71% in eco-friendly CLSM, and 65.45% in granular compacted fill. Cart-away sits at 30.82%, 39.82%, and 26.22%, while excavation comprises only 7.33%, 9.47%, and 6.24%, respectively. Compaction is negligible for both eco-friendly and conventional CLSM mixes, but it represents 2.10% of the compacted granular fill cost.

Table 6.3 presents a comparative analysis of the LCCA results, showcasing the percentage contributions of the different stages to the unit price and total price, encompassing excavation, cart away, filling, and compaction for the three backfilling materials.

Table 6.3 Contribution of each LCC phase to the unit and total price per linear trench

	Contribution of each LCC phase to the total price per cubic meter (%)		
List of stages	Types of backfilling materials		
	Conventional CLSM	Eco-Friendly CLSM	Granular compacted fill
Excavation	6.68%	9.02%	5.87%
Cart away	22.48%	30.33%	19.74%
Filling	70.83%	60.65%	72.08%
Compaction	0.00%	0.00%	2.31%
	Contribution of each LCC phase to the total price per linear trench (%)		
Excavation	7.33%	9.47%	6.24%
Cart away	30.82%	39.82%	26.22%
Filling	61.85%	50.71%	65.45%
Compaction	0.00%	0.00%	2.10%

These results emphasize that material selection predominantly influences the share of total life-cycle expenses during the filling stage, making eco-friendly CLSM the most cost-effective solution under the analyzed scenarios. By incorporating recycled materials such as IWA fine aggregate, concrete sludge powder, and GGBFS supernatant, which displace virgin materials, eco-friendly CLSM achieves a 36.5% reduction in filling stage expenses relative to the conventional CLSM mix.

6.4. Summary

This chapter presents the results and discussion of the life cycle assessment (LCA) and life cycle cost (LCC) comparative analysis, focusing on eco-friendly CLSM, conventional CLSM, and granular backfill across six environmental impact categories and direct cost analysis. The findings are examined within the context of existing literature.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1. Conclusion

This study investigated the fresh and hardened properties, durability, life cycle assessment, and life cycle costing analysis of eco-friendly CLSM, incorporating materials from fresh concrete waste, such as IWA fine aggregate and concrete sludge powder, with the industrial by-product ground granulated blast furnace slag, as sustainable alternatives to traditional ordinary Portland cement. Based on the comprehensive experimental phase conducted to develop eco-friendly CLSM mixes under various conditions, the following conclusions are drawn from the study.

7.1.1. Development of Optimized, Excavatable, and Eco-friendly CLSM

- Incorporating up to 20% concrete sludge powder enhances the stability of the eco-friendly CLSM mix by reducing bleeding and increasing its unconfined compressive strength. However, increasing the concrete sludge powder substitution beyond 20% decreases flowability below the acceptable limit, indicating that a 20% replacement is optimal for developing novel, eco-friendly CLSM.
- A comprehensive assessment of the excavability criteria, utilizing a 28-day unconfined compressive strength of 281.90 kN/m^2, a removability modulus of 0.67, and long-term strength evaluations at 56 and 91 days, revealed that 40 kg/m^3 was the optimal binder content for eco-friendly CLSM used in buried pipe backfilling applications.
- The use of super-retardant admixture demonstrated that increasing the geoliter 10 admixture dosages from 0% to 10% in eco-friendly CLSM at a binder content of 40 kg/m^3 significantly delayed the hardening process, reduced viscosity, and enhanced workability by improving flowability and wet density without substantially increasing bleeding.
- The water permeability tests on the optimal eco-friendly CLSM showed values of 3.07×10^{-4} cm/sec at 7 days and 1.62×10^{-4} cm/sec at 28 days, indicating that the water permeability of the eco-friendly CLSM mix decreased as the unconfined compressive strength increased.
- A leaching test revealed a hexavalent chromium value of 0.007 mg/L, which complies with environmental quality standards for soil, demonstrating the effectiveness of ground granulated blast furnace slag and returned concrete waste materials in reducing heavy metal leaching and ensuring the practical application of eco-friendly CLSM.

- The durability test of the optimal eco-friendly CLSM, subjected to twelve wetting and drying cycles, demonstrated high resistance to degradation at 28 days, with mass loss values of 11.77% and a residual compressive strength of 206.49 kN/m², exceeding the minimum strength requirement of 200 kN/m² for buried pipe backfilling. It indicates that the resistance of eco-friendly CLSM directly correlates with its compressive strength, where increased strength leads to reduced mass loss.
- The use of fully recycled, returned fresh concrete waste and industrial by-products in developing eco-friendly CLSM promotes efficient resource utilization and waste reduction, aligning with circular economic principles to minimize environmental impact by reducing landfill waste and easing the burden on ready-mixed concrete plants.

7.1.2. Life Cycle Assessment and Life Cycle Costing

- Eco-friendly CLSM is the most sustainable alternative across all six impact categories, including global warming, mineral resource scarcity, fossil resource scarcity, ozone formation, fine particulate matter formation, and terrestrial acidification, whereas granular compacted fill is the least efficient option.
- In economic terms, the analysis results indicate that eco-friendly CLSM can reduce the total life cycle cost per linear meter of trench by 53% compared to granular compacted fill and by 22.6% compared to conventional CLSM.
- Life cycle assessment confirms that eco-friendly CLSM made from returned concrete and industrial by-products improves resource efficiency, minimizes waste, and aligns with circular economy principles by diverting landfill waste and reducing the burden on ready-mixed concrete plants.
- The installation phase significantly contributes to the overall environmental impact, excluding the scarcity of mineral resources, underscoring the need for improvements in construction practices.

7.2. Recommendation for future works

CLSM has been used for decades primarily as a backfilling material and still holds significant potential for various other applications. Additional initiatives and research are necessary to enhance its properties, improve eco-friendliness, sustainability, and cost-effectiveness, thereby expanding the applicability of this approach. Based on the findings of this study, the following recommendations are proposed for practical application, and further research is required to improve the use of eco-friendly CLSM.

- Certain specifications for CLSM mixes exist; however, global acceptance is limited due to diverse waste resource usage and trial-and-error methods employed. Standardizing mix design, testing protocols, and guidelines can improve consistency and increase wider adoption. Establishing industry standards for CLSM is needed for the successful implementation of CLSM in construction and for building practitioner confidence.
- To compare the results of this study, future research could focus on improving the methodology by conducting a consequential Life Cycle Assessment (LCA) using commercially available databases, such as ecoinvent or the Inventory Database for Environmental Analysis (IDEA) of Japan. Additionally, these studies could assess the environmental and economic dimensions of each material type in comparison to soil, using either selected backfill material or excavated and reused soil onsite, while considering sensitivity analysis.
- Ready-mixed concrete manufacturers and future researchers can use the performance-based four-stage mix design methodology developed in this study as an initial guide for buried pipe backfilling applications. Future studies should aim to generalize this mix design approach shifting from traditional trial-and-error methods to a standardized, globally accepted framework.
- To enhance safety during excavation activities in areas with buried utilities, it is necessary to use colored CLSM as a backfill. Future investigations should focus on conducting thorough investigations to assess the effects of different color pigments on the properties of CLSM, ensuring its effectiveness and safety in practical applications. By prioritizing these recommendations, the construction industry can significantly improve safety protocols and minimize the risks associated with underground utilities.
- In buried pipe backfilling applications, the limited long-term strength gain of CLSM mixtures is significant, ensuring easy re-excavation in the event of a future pipe failure. Therefore, it is crucial to ensure the excavatability of CLSM using practical, on-site applications, rather than relying solely on indicators measured on specimens such as 28-day compressive strength, long-term strength, and the Removability Modulus. Hence, a more thorough study is needed to investigate the excavatability of CLSM with practical applications for the long term.
- Flotation of pipes is a key concern in high water table areas, especially during CLSM backfilling due to its fluid nature. Future studies should evaluate the effectiveness of mitigation measures such as earth anchors, concrete collars, and temporary ballast systems under realistic field conditions.

- Due to the complexity of materials utilized, future research should employ advanced characterization techniques, such as rheology, microscopy, and non-destructive testing to gain deeper insight into the reaction mechanisms and performance of eco-friendly CLSM with controlled material processing systems.
- Given the observed variability in the physical properties of IWA fine aggregates due to factors such as the nominal strength of the source return concrete and storage conditions, future research should focus on developing a standardized classification system for IWA fine aggregates.
- As a hybrid of concrete and geotechnical materials, CLSM often lacks focused attention. Future research should promote collaboration between the two fields to develop unified test methods and design standards, thereby supporting the broader adoption and proper evaluation of CLSM in practice.

7.3. Summary

This chapter provided a comprehensive conclusion and set of recommendations based on the experimental findings, life cycle assessment, and life cycle cost analysis of this study. The results underscore the viability of utilizing fully recycled, returned fresh concrete waste and industrial by-products in developing eco-friendly CLSM, offering competitive fresh and hardened properties, durability, and promoting efficient resource utilization and waste reduction, aligning with circular economic principles to minimize environmental impact by reducing landfill waste and easing the burden on ready-mixed concrete plants

REFERENCES

[1] L. Chen et al., "Conversion of waste into sustainable construction materials: A review of recent developments and prospects," Materials Today Sustainability, vol. 27, p. 100930, 2024/09/01/ 2024, doi: https://doi.org/10.1016/j.mtsust.2024.100930.

[2] L. F. Jiménez, J. A. Domínguez, and R. E. Vega-Azamar, "Carbon footprint of recycled aggregate concrete," Advances in civil engineering, vol. 2018, no. 1, p. 7949741, 2018.

[3] A. Kazaz and S. Ulubeyli, "Current methods for the utilization of the fresh concrete waste returned to batching plants," Procedia Engineering, vol. 161, pp. 42-46, 2016.

[4] G. Ferrari, M. Miyamoto, and A. Ferrari, "New sustainable technology for recycling returned concrete," Construction and Building Materials, vol. 67, pp. 353-359, 2014, doi: 10.1016/j.conbuildmat.2014.01.008.

[5] D. Xuan, C. S. Poon, and W. Zheng, "Management and sustainable utilization of processing wastes from ready-mixed concrete plants in construction: A review," Resources, Conservation and Recycling, vol. 136, pp. 238-247, 2018, doi: 10.1016/j.resconrec.2018.04.007.

[6] S. Desai, "Sustainable development and recycling of concrete aggregate," in Sustainable Construction: Use of Recycled Concrete Aggregate: Proceedings of the International Symposium organised by the Concrete Technology Unit, University of Dundee and held at the Department of Trade and Industry Conference Centre, London, UK on 11–12 November 1998, 1998: Thomas Telford Publishing, pp. 381-388.

[7] Q. Zhao, W. Gao, Y. Su, T. Wang, and J. Wang, "How can C&D waste recycling do a carbon emission contribution for construction industry in Japan city?," Energy and Buildings, vol. 298, p. 113538, 2023.

[8] H. A. Ali, B. Zhang, C. Xiao, B. Zhao, D. Xuan, and C. S. Poon, "Valorization of fine recycled C&D aggregate and incinerator bottom ash for the preparation of controlled low-strength material (CLSM)," Cleaner Waste Systems, vol. 3, p. 100061, 2022.

[9] B. Sealey, P. S. Phillips, and G. Hill, "Waste management issues for the UK ready-mixed concrete industry," Resources, Conservation and Recycling, vol. 32, no. 3-4, pp. 321-331, 2001.

[10] V. W. Tam and C. M. Tam, "Economic comparison of recycling over-ordered fresh concrete: A case study approach," Resources, Conservation and Recycling, vol. 52, no. 2, pp. 208-218, 2007.

[11] R. Wang and Y. X. Zhang, "Recycling Fresh Concrete Waste: A Review," Structural Concrete, vol. 19, no. 6, pp. 1939-1955, 2018, doi: 10.1002/suco.201800057.

[12] A. Katz and K. Kovler, "Utilization of industrial by-products for the production of controlled low strength materials (CLSM)," Waste Management, vol. 24, no. 5, pp. 501-512, 2004.

[13] Mapei. "Re-Con Zero Evo: how concrete becomes sustainable." Realtà Mapei International. https://www.mapei.com/it/en/realta-mapei/detail/re-con-zero-evo (accessed May 2, 2025).

[14] J. Zhang and T. Fujiwara, "Concrete sludge powder for soil stabilization," Transportation research record, vol. 2026, no. 1, pp. 54-59, 2007.

[15] M. Audo, P.-Y. Mahieux, and P. Turcry, "Utilization of sludge from ready-mixed concrete plants as a substitute for limestone fillers," Construction and Building Materials, vol. 112, pp. 790-799, 2016.

[16] T. KUSUI, N. AMANO, Y. NOTO, M. TATEDA, and H. ITO, "Study on recycle of concrete sludge produced at concrete mills in Toyama Prefecture," Journal of Ecotechnology Research, vol. 17, no. 1, pp. 39-43, 2013.

[17] P. R. de Matos, L. R. Prudencio Jr, R. Pilar, P. J. P. Gleize, and F. Pelisser, "Use of recycled water from mixer truck wash in concrete: Effect on the hydration, fresh and hardened properties," Construction and Building Materials, vol. 230, p. 116981, 2020.

[18] ACI Committee 229, ACI 229R-13; Report on Controlled Low-Strength Materials, . American Concrete Institute (ACI): Farmington Hills, MI, USA, 2013., 2013.

[19] S. K. Parhi, S. Dwibedy, S. Panda, and S. K. Panigrahi, "A comprehensive study on controlled low strength material," Journal of Building Engineering, vol. 76, p. 107086, 2023.

[20] K. J. Folliard, Development of a recommended practice for use of controlled low-strength material in highway construction. Transportation Research Board, 2008.

[21] M. Etxeberria, J. Ainchil, M. E. Pérez, and A. González, "Use of recycled fine aggregates for Control Low Strength Materials (CLSMs) production," Construction and Building Materials, vol. 44, pp. 142-148, 2013.

[22] Q. Munir, V. Lahtela, T. Kärki, and A. Koivula, "Assessing life cycle sustainability: A comprehensive review of concrete produced from construction waste fine fractions," Journal of Environmental Management, vol. 366, p. 121734, 2024.

[23] M. U. Hossain, D. Xuan, and C. S. Poon, "Sustainable management and utilisation of concrete slurry waste: A case study in Hong Kong," Waste Management, vol. 61, pp. 397-404, 2017.

[24] L. Zhang, Q. Hu, Q. Luo, D. P. Connolly, and T. Wang, "Assessing Workability of Ready-Mixed Soils Derived from Excess Spoil," Journal of Materials in Civil Engineering, vol. 36, no. 10, p. 04024331, 2024.

[25] M. Lachemi, M. Şahmaran, K. M. A. Hossain, A. Lotfy, and M. Shehata, "Properties of controlled low-strength materials incorporating cement kiln dust and slag," Cement and Concrete Composites, vol. 32, no. 8, pp. 623-629, 2010, doi: 10.1016/j.cemconcomp.2010.07.011.

[26] Public Works Research Institute; Technical Manual for Liquefied Stabilized Soil (in Japanese), 2nd ed.; Gihodo Publishing Co., Ltd.: Tokyo, Japan, 2007.

[27] W. E. Brewer and J. O. Hurd, "Economic Considerations When Using Controlled Low-Strength Material (CLSM-CDF) as Backfill," Transportation Research Record, no. 1315, 1991.

[28] J. Kaneshiro, S. Navin, L. Wendel, and H. Snowden, "Controlled Low Strength Material for Pipeline Backfill?Specifications, Case Histories and Lessons Learned," in Pipelines 2001, (Proceedings, 2012, pp. 1-13.

[29] T. H. W. Baker, Frost penetration in flowable fill used in pipe trench backfill. ASTM International, 1998.

[30] H. Todres and P. E. Baker, "UTILITIES CONDUCT RESEARCH IN PAVEMENT RESTORATION," APWA Reporter, vol. 63, no. 10, 1996.

[31] H. Baker and L. Goodrich, "Trench backfill and reinstatement," in 46th Annual Conference of the Western Canada Water and Wastewater Association, Winnipeg, 1994.

[32] J. Emery and T. Johnston, "Unshrinkable fill for utility cut restorations," Special Publication, vol. 93, pp. 187-212, 1986.

[33] W. Brewer, "Durability factors affecting CLSM," Special Publication, vol. 150, pp. 39-52, 1994.

[34] A. Howard, Pipeline installation. 1996.

[35] A. Howard[1], "Proposed standard practice for installing buried pipe using flowable fill," The design and application of controlled low-strength materials (flowable fill), vol. 1331, p. 285, 1998.

[36] J. L. Hitch, Test methods for controlled low-strength material (CLSM): past, present, and future. ASTM International, 1998.

[37] "The Cincinnati Gas & Electric Company, 1992, Special Report Controlled Low Strength Material (CLSM) for Ready Mixed Concrete Producers, Brewer & Associates, Toledo, Ohio.."

[38] T. Q. Tran, Y.-s. Kim, L. C. Dang, and T. M. Do, "A state-of-the-art review on the utilization of new green binders in the production of controlled low-strength materials," Construction and Building Materials, vol. 393, p. 132078, 2023.

[39] Japan Industrial Standard (JIS). Portland Cement; JIS R 5210:2009; JIS: Tokyo, Japan, 2009. (In Japanese).

[40] T. Horiguchi, R. Fujita, and K. Shimura, "Applicability of controlled low-strength materials with incinerated sewage sludge ash and crushed-stone powder," Journal of materials in civil engineering, vol. 23, no. 6, pp. 767-771, 2011.

[41] Japan Industrial Standard (JIS). Portland blast-furnace slag cement; JIS R 5211:2009; JIS: Tokyo, Japan, 2009. (In Japanese)

[42] T. Raghavendra and B. Udayashankar, "Flow and strength characteristics of CLSM using ground granulated blast furnace slag," Journal of materials in civil engineering, vol. 26, no. 9, p. 04014050, 2014.

[43] T. R. Naik and B. Ramme, "Low-strength concrete and controlled low-strength material (CLSM) produced with class F fly ash," Special Publication, vol. 150, pp. 1-14, 1994.

[44] M. Lachemi, K. Hossain, M. Shehata, and W. Thaha, "Controlled low strength materials incorporating cement kiln dust from various sources," Cement and Concrete Composites, vol. 30, no. 5, pp. 381-392, 2008.

[45] W.-C. Wang, J.-C. Xue, C.-Y. Huang, and H.-C. Chang, "Incineration bottom ash as aggregate for controlled low strength materials: Implications and coping strategies," Journal of Advanced Concrete Technology, vol. 21, no. 11, pp. 837-850, 2023.

[46] J. M. Khatib, "Properties of concrete incorporating fine recycled aggregate," Cement and concrete research, vol. 35, no. 4, pp. 763-769, 2005.

[47] S. Achtemichuk, J. Hubbard, R. Sluce, and M. H. Shehata, "The utilization of recycled concrete aggregate to produce controlled low-strength materials without using Portland cement," Cement and Concrete Composites, vol. 31, no. 8, pp. 564-569, 2009.

[48] W.-T. Lin, T.-L. Weng, A. Cheng, S.-J. Chao, and H.-M. Hsu, "Properties of controlled low strength material with circulating fluidized bed combustion ash and recycled aggregates," Materials, vol. 11, no. 5, p. 715, 2018.

[49] M. Funayama, et al.,, "Investigation on Physical Properties of Liquefied Stabilized Soil Using Aggregate Made from Returned Concrete, in The 45th JCI Technical Conference. 2023, Japan Concrete Institute Kyushu, Japan.."

[50] J. Botton, L. L. Stankievicz, R. Gheller, J. M. M. de Mello, F. Dalconton, and S. B. Onofre, "Reuse of the Concrete Mixer Truck Wash Water in the Production of Concrete-A Clean Production Proposal," International Journal of Advanced Engineering Research and Science, vol. 5, no. 3, p. 237391, 2018.

[51] N. Su, B. Miao, and F.-S. Liu, "Effect of wash water and underground water on properties of concrete," Cement and Concrete Research, vol. 32, no. 5, pp. 777-782, 2002/05/01/ 2002, doi: https://doi.org/10.1016/S0008-8846(01)00762-1.

[52] A. Blanco, P. Pujadas, S. Cavalaro, and A. Aguado, "Methodology for the design of controlled low-strength materials. Application to the backfill of narrow trenches," Construction and Building Materials, vol. 72, pp. 23-30, 2014.

[53] V. Hospodarova, J. Junak, and N. Stevulova, "Color pigments in concrete and their properties," Pollack Periodica, vol. 10, no. 3, pp. 143-151, 2015.

[54] P. J. Tikalsky, E. Smith, and R. Regan, "Proportioning spent casting sand in controlled-low strength materials," Materials Journal, vol. 95, no. 6, pp. 740-746, 1998.

[55] K. J. Kowalski, Z. Yang, J. Olek, and T. Nantung, "Development of specification for accelerated approval process of flowable fill mixtures," Journal of materials in civil engineering, vol. 21, no. 12, pp. 740-748, 2009.

[56] M. Frías, M. S. De Rojas, N. García, and M. P. d. Luxán, "Contribution of toxic elements: Hexavalent chromium in materials used in the manufacture of cement," Cement and Concrete Research, vol. 24, no. 3, pp. 533-541, 1994.

[57] W. A. Klemm, "Hexavalent chromium in Portland cement," Cement, Concrete, and Aggregates, vol. 16, no. 1, pp. 43-47, 1994.

[58] C. Eckbo, G. Okkenhaug, and S. E. Hale, "The effects of soil organic matter on leaching of hexavalent chromium from concrete waste: Batch and column experiments," Journal of Environmental Management, vol. 309, p. 114708, 2022.

[59] Z. Huang, T. Tong, H. Liu, and W. Qi, "Properties of soil-based flowable fill under drying–wetting and freeze–thaw actions," Sustainability, vol. 15, no. 3, p. 2390, 2023.

[60] "Osaka Hyogo Ready-Mixed Concrete Industrial Association: Manual for the Effective Utilization of Recycled Aggregates - IWA System Edition (in Japanese)."

[61] " Osaka Hyogo Ready-Mixed Concrete Industry Association: Complete recycling of returned concrete “IWA System Edition (in Japanese) - p7-14, 2014. ." [Online]. Available: http://osakahyogokouso.or.jp/old/wp-content/uploads/IWA.pdf

[62] M. Kurinobu, "Recycled aggregates - A complete recycling system for returned concrete: From the manual for effective use of recycled aggregates - IWA System Edition (in Japanese)," Journal of concrete technology, vol. 34, no. 9, pp. 9-22, 2015.

[63] T.-C. Ling, S. K. Kaliyavaradhan, and C. S. Poon, "Global perspective on application of controlled low-strength material (CLSM) for trench backfilling – An overview," Construction and Building Materials, vol. 158, pp. 535-548, 2018, doi: 10.1016/j.conbuildmat.2017.10.050.

[64] A. J. Finney, E. F. Shorey, and J. Anderson, "Use of native soil in place of aggregate in controlled low strength material (CLSM)," in Pipelines 2008: Pipeline asset management: Maximizing performance of our pipeline infrastructure, 2008, pp. 1-13.

[65] J. Kaneshiro, S. Navin, L. Wendel, and H. Snowden, "Controlled Low Strength Material for Pipeline Backfillâ€” Specifications, Case Histories and Lessons Learned," in Pipelines 2001: Advances in Pipelines Engineering and Construction, 2001, pp. 1-13.

[66] H. Liu, Y. Xiao, K. Liu, Y. Zhu, and P. Zhang, "Numerical simulation on backfilling of buried pipes using controlled low strength materials," Applied Sciences, vol. 12, no. 14, p. 6901, 2022.

[67] PPI et al., 21st Century Drainage Solutions: PPI Drainage Handbook. PPI, Plastics Pipe Institute, 2021.

[68] A. Standard, "D2321 Standard practice for the underground installation of thermoplastic pipe for sewers and other gravity-flow applications," West Conshohocken, PA: United States: ASTM International, vol. 290, 2014.

[69] C. A. Lowitz and G. DeGroot, "Soil-Cement Pipe Bedding: Canadian River Aqueduct," Journal of the Construction Division, vol. 94, no. 1, pp. 17-33, 1968, doi: doi:10.1061/JCCEAZ.0000211.

[70] R. L. Larsen, "Sound uses of CLSMs in the environment," Concrete International, vol. 12, no. 7, pp. 26-29, 1990.

[71] J. Boschert and J. Butler, "CLSM as a pipe bedding: Computing predicted load using the modified Marston equation," in Pipelines 2013: Pipelines and Trenchless Construction and Renewals—A Global Perspective, 2013, pp. 1201-1212.

[72] Y. Shigematsu, S. Inazumi, R. Hashimoto, and H. Yamauchi, "Experimental study on properties of liquefied stabilized soil produced with different types of solidifiers and thickeners," Case Studies in Construction Materials, vol. 19, p. e02407, 2023/12/01/ 2023, doi: https://doi.org/10.1016/j.cscm.2023.e02407.

[73] K. Horii, N. Tsutsumi, T. Kato, Y. Kitano, and K. Sugahara, "Overview of iron/steel slag application and development of new utilization technologies," Nippon Steel & Sumitomo Metal Technical Report, vol. 109, no. 109, pp. 5-11, 2015.

[74] P.-C. Aïtcin, High performance concrete. CRC press, 1998.

[75] Japanese Industrial Standards (JIS) A 5308, Ready-Mixed Concrete. Japanese Standards Association; , J. S. A. (JSA), Tokyo, Japan, 2019.

[76] M. Lachemi, M. Şahmaran, K. Hossain, A. Lotfy, and M. Shehata, "Properties of controlled low-strength materials incorporating cement kiln dust and slag," Cement and Concrete Composites, vol. 32, pp. 623-629, 09/01 2010, doi: 10.1016/j.cemconcomp.2010.07.011.

[77] M. F. Test, "Japan Highway Public Corporation Test Method," JHS A, pp. 313-1992, 1992.

[78] A. JIS, "1216; Method for Unconfined Compression Test of Soils," Japanese Industrial Standard Association: Tokyo, Japan, 2020.

[79] Japanese Industrial Standards (JIS) K 0102; Testing Methods for Industrial Wastewater, Japanese Standards Association (JSA), 2019.

[80] A. ASTM D559, "Standard test methods for wetting and drying compacted soil-cement mixtures," Conshohocken, PA (USA), 2003.

[81] K. Harichane, M. Ghrici, and S. Kenai, "Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study," Environmental earth sciences, vol. 66, pp. 2197-2205, 2012.

[82] X. Wu, W. Jiang, and D. M. Roy, "Early activation and properties of slag cement," Cement and Concrete Research, vol. 20, no. 6, pp. 961-974, 1990.

[83] T. R. Naik, R. N. Kraus, R. Siddique, and Y.-M. Chun, Properties of controlled low-strength materials made with wood fly ash. ASTM International, 2004.

[84] A. Basha and W. Mansour, "Variation of the hydraulic conductivity and the mechanical characteristics of plastic concrete with time," International Journal of Concrete Structures and Materials, vol. 17, no. 1, p. 27, 2023.

[85] T. R. Naik and S. S. Singh, "Permeability of flowable slurry materials containing foundry sand and fly ash," Journal of Geotechnical and Geoenvironmental Engineering, vol. 123, no. 5, pp. 446-452, 1997.

[86] E. Ganjian, P. Claisse, M. Tyrer, and A. Atkinson, "Factors affecting measurement of hydraulic conductivity in low-strength cementitious materials," Cement and concrete research, vol. 36, no. 12, pp. 2109-2114, 2006.

[87] D. E. Macphee and F. P. Glasser, "Immobilization science of cement systems," MRS bulletin, vol. 18, no. 3, pp. 66-71, 1993.

[88] R. Packard and G. Chapman, "Developments in durability testing of soil-cement mixtures," Highway Research Record, no. 36, 1963.

[89] P. C. Association, "Soil-cement laboratory handbook," (No Title), 1959.

[90] I. Josa, A. Petit-Boix, M. d. M. Casanovas-Rubio, P. Pujadas, and A. De la Fuente, "Environmental and economic impacts of combining backfill materials for novel circular narrow trenches," Journal of environmental management, vol. 341, p. 118020, 2023.

[91] I. P. Segura, N. Ranjbar, A. J. Damø, L. S. Jensen, M. Canut, and P. A. Jensen, "A review: Alkali-activated cement and concrete production technologies available in the industry," Heliyon, vol. 9, no. 5, 2023.

[92] T. Manh Do, G.-O. Kang, and Y.-s. Kim, "Development of a new cementless binder for controlled low strength material (CLSM) using entirely by-products," Construction and Building Materials, vol. 206, pp. 576-589, 2019/05/10/ 2019, doi: https://doi.org/10.1016/j.conbuildmat.2019.02.088.

[93] N. K. Lee, H. K. Kim, I. S. Park, and H. K. Lee, "Alkali-activated, cementless, controlled low-strength materials (CLSM) utilizing industrial by-products," Construction and Building Materials, vol. 49, pp. 738-746, 2013.

[94] R. Xiao, P. Polaczyk, X. Jiang, M. Zhang, Y. Wang, and B. Huang, "Cementless controlled low-strength material (CLSM) based on waste glass powder and hydrated lime: Synthesis, characterization and thermodynamic simulation," Construction and Building Materials, vol. 275, p. 122157, 2021/03/15/ 2021, doi: https://doi.org/10.1016/j.conbuildmat.2020.122157.

[95] E. Hateu, A. Hosoda, and P. Ngoc, Mitsuya, Miyamoto, "Development of Eco-Friendly Controlled Low-Strength Material Utilizing Fresh Concrete Waste and By-Products," 2025, 306-311.

[96] U. Salini, A. Parayil, B. Diya, and L. Dev, "Use of fly ash and quarry waste for the production of the controlled low strength material," Construction and Building Materials, vol. 392, p. 131924, 2023.

[97] P. Tikalsky, M. Gaffney, and R. Regan, "Properties of controlled low-strength material containing foundry sand," Materials Journal, vol. 97, no. 6, pp. 698-702, 2000.

[98] S. K. Kaliyavaradhan, T.-C. Ling, M.-Z. Guo, and K. H. Mo, "Waste resources recycling in controlled low-strength material (CLSM): A critical review on plastic properties," Journal of Environmental Management, vol. 241, pp. 383-396, 2019.

[99] S. Simon, L. Zanoni, A. Young, P. Hulsebosch, J. K. Chetri, and K. R. Reddy, "Sustainability Assessment of Controlled Low Strength Materials Utilizing Various Industrial Waste Materials," in Proceedings of Indian Geotechnical and Geoenvironmental Engineering Conference (IGGEC) 2021, Vol. 1, (Lecture Notes in Civil Engineering, 2023, ch. Chapter 1, pp. 3-15.

[100] A. Mishra, S. K. Das, and K. R. Reddy, "Environmental Sustainability Assessment of Alternative Controlled Low Strength Materials as a Fill Material," in Geoenvironmental and Geotechnical Issues of Coal Mine Overburden and Mine Tailings, (Springer Transactions in Civil and Environmental Engineering, 2024, ch. Chapter 9, pp. 133-146.

[101] I. Josa, A. Petit-Boix, M. M. Casanovas-Rubio, P. Pujadas, and A. de la Fuente, "Environmental and economic impacts of combining backfill materials for novel circular narrow trenches," J Environ Manage, vol. 341, p. 118020, Sep 1 2023, doi: 10.1016/j.jenvman.2023.118020.

[102] K. Kawai, T. Sugiyama, K. Kobayashi, and S. Sano, "Inventory data and case studies for environmental performance evaluation of concrete structure construction," Journal of Advanced Concrete Technology, vol. 3, no. 3, pp. 435-456, 2005.

[103] K. Kawai, A. Fujiki, Y. Aoki, and Y. Iwatani, "Preparation of Inventory Data for Environmental Performance Evaluation of Concrete and Concrete Structures," in Proceedings of Second International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy,(To be published), 2010.

[104] Y. Ishii et al., "Test Construction of Low-Carbon Pavement Using Materials Containing Absorbed Carbon Dioxide (written in Japanese)," Pacific Cement Research Report vol. 2024, no. 187, pp. 34-43, 2025, doi: 10.69252/taiheiyoresearch.2024.187_34.

[105] E. Presura and L. D. Robescu, "Energy use and carbon footprint for potable water and wastewater treatment," Proceedings of the International Conference on Business Excellence, vol. 11, no. 1, pp. 191-198, 2017, doi: 10.1515/picbe-2017-0020.

[106] Y. Shimizu, S. Dejima, and K. Toyosada, "The CO2 Emission Factor of Water in Japan," Water, vol. 4, no. 4, pp. 759-769, 2012, doi: 10.3390/w4040759.

[107] AASHTO, "Bridge design specifications," 1998.

[108] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H.-J. Klüppel, "The new international standards for life cycle assessment: ISO 14040 and ISO 14044," The international journal of life cycle assessment, vol. 11, pp. 80-85, 2006.

[109] H.-J. Klüppel, "ISO 14041: Environmental management—life cycle assessment—goal and scope definition—inventory analysis," The International Journal of life cycle assessment, vol. 3, no. 6, pp. 301-301, 1998.

[110] S.-O. Ryding, "ISO 14042 Environmental management• Life cycle assessment• life cycle impact assessment," The International Journal of life cycle assessment, vol. 4, no. 6, pp. 307-307, 1999.

[111] H. Lecouls, "ISO 14043: Environmental management· life cycle assessment· life cycle interpretation," The International Journal of Life Cycle Assessment, vol. 4, no. 5, pp. 245-245, 1999.

[112] M. A. J. Huijbregts et al., "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," The International Journal of Life Cycle Assessment, vol. 22, no. 2, pp. 138-147, 2016, doi: 10.1007/s11367-016-1246-y.

[113] F. Du, G. J. Woods, D. Kang, K. E. Lansey, and R. G. Arnold, "Life cycle analysis for water and wastewater pipe materials," Journal of Environmental Engineering, vol. 139, no. 5, pp. 703-711, 2013.

[114] E. Vahidi, E. Jin, M. Das, M. Singh, and F. Zhao, "Environmental life cycle analysis of pipe materials for sewer systems," Sustainable Cities and Society, vol. 27, pp. 167-174, 2016.

[115] BEDEC, "Catalonia Institute of Construction Technology," BEDEC ITEC Materials Database., 2024.

[116] B. Steen, "Environmental costs and benefits in life cycle costing," Management of Environmental Quality: An International Journal, vol. 16, no. 2, pp. 107-118, 2005.

[117] S. Jian, C. Cheng, Y. Lv, C. Wang, H. Tan, and B. Li, "Preparation and evaluation of high-fluid backfill materials from construction spoil," Construction and Building Materials, vol. 345, p. 128370, 2022.

[118] B. W. Meade, D. Q. Hunsucker, and M. D. Stone, "Evaluation of CLSM (Flowable Fill) for trench backfill," Kentucky Transportation Center, College of Engineering, University of Kentucky, 1993.

[119] Construction & material costs in Japan: kensetsu bukka eibun daijesutoban 5. 建設物価調査会, 1997.

[120] A. Šiškina, A. Juodis, and R. Apanavičienė, "Evaluation of the Competitiveness of Construction Company Overhead Costs," Journal of Civil Engineering and Management, vol. 15, no. 2, pp. 215-224, 2009, doi: 10.3846/1392-3730.2009.15.215-224.

[121] B. Wang, J. Yuan, and K. Z. Ghafoor, "Research on Construction Cost Estimation Based on Artificial Intelligence Technology," Scalable Computing Practice and Experience, vol. 22, no. 2, pp. 93-104, 2021, doi: 10.12694/scpe.v22i2.1868.

[122] H.-H. Wang, S.-W. Weng, A. A. Gansonre, and W.-C. Wang, "Developing an Ontology-Based Representation Framework for Establishing Cost Analysis Knowledge Base for Construction Work Items," 2014, doi: 10.22260/isarc2014/0050.

[123] K. B. Chosakai, "Gekkan Kensetsu Bukka [Monthly Journal of Construction and Material Cost]," 2025. [Online]. Available: https://www.ribc.or.jp/research/pdf/tankashiryo/4/128.pdf

[124] J. Houghton, "Global warming," Reports on progress in physics, vol. 68, no. 6, p. 1343, 2005.

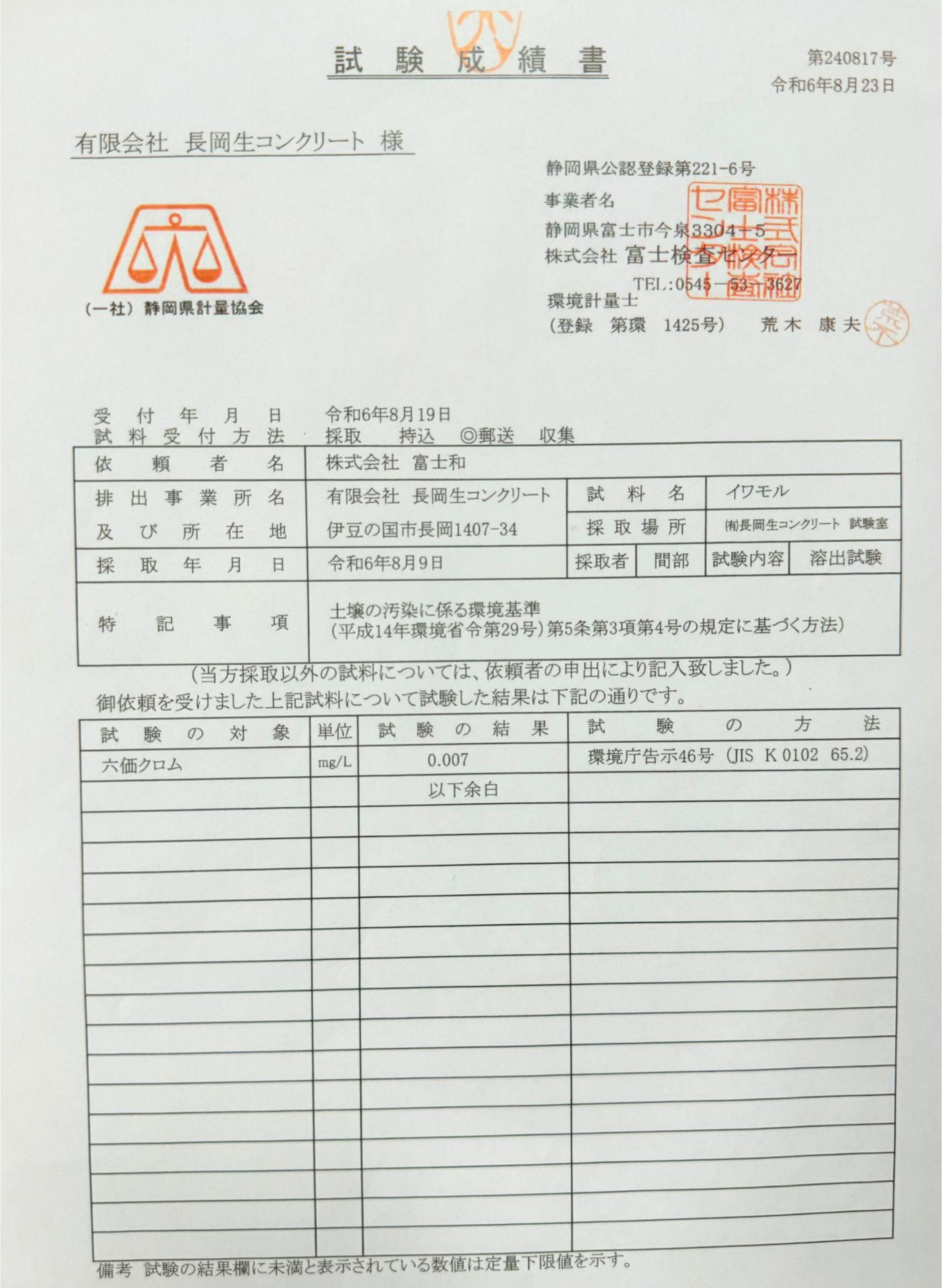
[125] A. Mishra, S. K. Das, and K. R. Reddy, "Environmental Sustainability Assessment of Alternative Controlled Low Strength Materials as a Fill Material," in Geoenvironmental and Geotechnical Issues of Coal Mine Overburden and Mine Tailings: Springer, 2023, pp. 133-146.

[126] P. H. Dalal, M. Patil, K. K. Iyer, and T. N. Dave, "Sustainable controlled low strength material from waste materials for infrastructure applications: State-of-the-art," Journal of Environmental Management, vol. 342, p. 118284, 2023.

[127] L. R. Garcez, C. E. T. Balestra, N. B. R. Monteiro, J. de Almeida Melo Filho, and M. A. R. Gil, "Mechanical strength and Life Cycle Assessment (LCA) of soil-cement: comparison between mixtures of soil with ASTM type III cement, LC3, and the incorporation of by products and agroindustrial residues," Construction and Building Materials, vol. 411, p. 134331, 2024.

[128] P. S. Rosman, M. A. A. Samah, K. Yunus, and M. Hussain, "Particulate matter (PM 2.5) at construction site: A review," Int. J. Recent Technol. Eng, vol. 8, no. 1C2, pp. 255-259, 2019.

APPENDIX A: HEXAVALENT CHROMIUM DETECTION TEST RESULT



試験成績書

第240817号
令和6年8月23日

有限会社 長岡生コンクリート 様

（一社）静岡県計量協会

静岡県公認登録第221-6号
事業者名
静岡県富士市今泉3304－5
株式会社 富士検査センター
TEL：0545－53－3627
環境計量士
（登録 第環 1425号） 荒木 康夫

受付年月日 令和6年8月19日
試料受付方法 採取 持込 ◎郵送 収集

依頼者名	株式会社 富士和				
排出事業所名及び所在地	有限会社 長岡生コンクリート 伊豆の国市長岡1407-34	試料名		イワモル	
		採取場所		㈲長岡生コンクリート 試験室	
採取年月日	令和6年8月9日	採取者	間部	試験内容	溶出試験
特記事項	土壌の汚染に係る環境基準 （平成14年環境省令第29号）第5条第3項第4号の規定に基づく方法）				

（当方採取以外の試料については、依頼者の申出により記入致しました。）
御依頼を受けました上記試料について試験した結果は下記の通りです。

試験の対象	単位	試験の結果	試験の方法
六価クロム	mg/L	0.007	環境庁告示46号（JIS K 0102 65.2）
		以下余白	

備考 試験の結果欄に未満と表示されている数値は定量下限値を示す。

一般社団法人 静岡県計量協会 承認様式 第302号

APPENDIX B: EMISSION INVENTORY DATA

Items	Unit (*)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
i. Emission Inventory Data for Energy Used for Operation					
Electricity	kWh	0.407	0.00013	0.00016	0.00003
Light oil for truck	L	2.64	0.00204	0.01977	0.00166
Light oil for equipment	L	2.64	0.00204	0.03961	0.00201
Coal (imported)	kg	2.36	-	-	-
Heavy oil (Type A)	L	2.77	0.013	0.00238	0.003
Heavy oil (Type C)	L	2.97	0.0564	-	-
Petroleum coke	kg	3.31	-	-	-
Gasoline	L	2.31	0.00059	-	-
ii. Emission Inventory Data for Transportation					
Truck Diesel (20t)	km.t	0.0714	0.0000549	0.000534	0.0000448
Dump truck Diesel (10t)	km.t	0.106	0.0000836	0.000811	0.0000681
Agitator truck (0.8-0.9m^3)	km.t	0.378	0.000297	0.00288	0.000242
iii. Emission Inventory Data for Constituent Materials					
Ordinary Portland Cement	t	766.6	0.122	1.55	0.0358
Fine aggregate	t	3.7	0.00860	0.00586	0.00199
Tap water	m^3	0.59	-	-	-
Blast furnace slag	t	26.5	0.00836	0.0102	0.00169
IWA fine aggregate	t	2.81	0.00120	0.0164	0.00119
Concrete sludge powder	t	-208	-	-	-
Supernatant water	m^3	0.0576	-	-	-
Crushed gravel	t	2.9	0.00607	0.00415	0.00141
Manufactured sand	t	3.7	0.00860	0.00586	0.00199
iv. Emission Inventory Data for Construction					
Backhoe Excavator (0.6m^3)	h	51.7	0.0398	0.774	0.0393
Concrete mixer (1.5m^3)	m^3	0.73	0.000235	0.000289	0.0000542
Agitator truck (0.8-0.9m^3)	h	10.0	0.00769	0.0747	0.00628
Vibrating tamper	h	2.1	0.000000451	0.0000132	0.000000489
v. Emission Inventory Data for Disposal and Recycling					
Leachate-controlled type landfill	t	3.3	0.00447	0.0255	0.00198

APPENDIX C: LIFE CYCLE COSTING (LCC) ANALYSIS

Appendix C-1: Excavation Rate Analysis

1.0 EXCAVATION

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project: Trench Backfilling Materials Life Cycle Cost (LCC)
Work Item: (1.1) Trench excavation up to 2 m deep, in soft soil, with a backhoe loader and mechanical loading of the excavated material.
Targeted Output Quantity: 1 m^3 Result: 1499.16 ¥/m

Material Cost (1:01)					**Labor Cost (1:02)**						**Equipment Cost (1:03)**				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hour Cos
					Equipment Operator	1	1	0.08	3638	291.04	Backhoe Excavator with fuel	1	0.1208	7000	845.
					Site Supervisor	1	0.5	0.08	5813	232.52					
					Daily Laborer	1	1	0.04	3250	130					
Total (1:01)					Total (1:02)					653.56	Total (1:03)				845.

A= Materials Unit Cost	0	¥/m^3	B= Manpower Unit Cost	654	¥/m^3	C= Equipment Unit Cost	845.60 ¥/m

Direct Cost of Work Item = A+B+C =		1499.16	¥/m
Overhead Cost:	0%	0.00	¥/m
Profit Cost:	0%	0.00	¥/m
Total :		1499.16	¥/m
VAT	0%	0	¥/m
Total unit cost:		1499.16	¥/m

Notes:
UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision
* Inclusive of transporting, loading and unloading, handling, etc.
** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.

Appendix C-2: Cart Away Rate Analysis

2.0 CART AWAY

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project: Trench Backfilling Materials Life Cycle Cost (LCC)
Work Item: (2.1) Hauling surplus excavated material 5.4 km away
Targeted Output Quantity: 1 m^3

Result: 5042.53 ¥/m^3

Material Cost (1:01)					Labor Cost (1:02)						Equipment Cost (1:03)				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hourly Cost
Surplus Soil Disposal	m^3	1	4500	4500	Equipment Operator	1	1	0.0069	3638	25.10	Backhoe Loader with fuel	1	0.0069	7000	48.3
					Truck Driver	1	1	0.015	3275	49.13	Dump truck (10t) with fuel	1	0.056	7500	420
Total (1:01)				4500	Total (1:02)					74.23	Total (1:03)				468.3

A= Materials Unit Cost 4500 ¥/m^3

B= Manpower Unit Cost 74.23 ¥/m^3

C= Equipment Unit Cost 468.3 ¥/m^3

Direct Cost of Work Item = A+B+C =		5042.53	¥/m^3
Overhead Cost:	0%	0.00	¥/m^3
Profit Cost:	0%	0.00	¥/m^3
Total :		5042.53	¥/m^3
VAT	0%	0	¥/m^3
Total unit cost:		5042.53	¥/m^3

Notes:

UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision
* Inclusive of transporting, loading and unloading, handling, etc.
** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.

Appendix C-3: Conventional CLSM Filling Rate Analysis

3.0 FILLING

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project: Trench Backfilling Materials Life Cycle Cost (LCC)
Work Item: (3.1) Conventional CLSM
Targeted Output Quantity: 1 m^3

Result: 15887.40 ¥/m^3

Material Cost (1:01)					**Labor Cost (1:02)**						**Equipment Cost (1:03)**				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hourly Cost
OPC Cement	kg	40	19	740	Site Supervisor	1	0.5	0.0672	5813	195.3168	Concrete mixer (1.5m^3)	1	0.336	4688.00	1575.17
Sand	kg	1604	6.50	10426	Daily Laborer	1	1	0.025	3250	81.25	Agitator truck (0.8-0.9m^3) with fuel	1	0.14	7500.00	1050
Tap Water	m^3	0.347	400	139	Mixer Operator	1	1	0.336	3638	1222.368					
					Agitator truck driver	1	1	0.14	3275	458.5					
Total (1:01)				11304.80	Total (1:02)					1957.43	Total (1:03)				2625.17

A= Materials Unit Cost	11304.80	¥/m^3	B= Manpower Unit Cost	1957.43	¥/m^3	C= Equipment Unit Cost	2625.17 ¥/m^3

Direct Cost of Work Item = A+B+C =		15887.40	¥/m^3
Overhead Cost:	0%	0.00	¥/m^3
Profit Cost:	0%	0.00	¥/m^3
Total :		15887.40	¥/m^3
VAT	0%	0	¥/m^3
Total unit cost:		15887.40	¥/m^3

Notes:
UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision
* Inclusive of transporting, loading and unloading, handling, etc.
** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.

Appendix C-4: Eco-Friendly CLSM Filling Rate Analysis

3.0 FILLING

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project:	Trench Backfilling Materials Life Cycle Cost (LCC)
Work Item: (3.2)	Eco-Friendly CLSM
Targeted Output Quantity:	1 m^3

Result: 10082.60 ¥/m^3

Material Cost (1:01)					Labor Cost (1:02)						Equipment Cost (1:03)				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hourly Cost
GGBFS	kg	40	15	580	Site Supervisor	1	0.5	0.0672	5813	195.3168	Concrete mixer (1.5m^3)	1	0.336	4688.00	1575.17
IWA Fine Aggregate	kg	984	4	3936	Daily Laborer	1	1	0.025	3250	81.25	Agitator truck (0.8-0.9m^3) with fuel	1	0.14	7500.00	1050
Sludge Powder	kg	246	4	984	Mixer Operator	1	1	0.336	3638	1222.368					
Supernatant Water	m^3	0.347	0	0	Agitator truck driver	1	1	0.14	3275	458.5					
Total (1:01)				5500	Total (1:02)					1957.43	Total (1:03)				2625.17

A= Materials Unit Cost 5500 ¥/m^3

B= Manpower Unit Cost 1957.43 ¥/m^3

C= Equipment Unit Cost 2625.17 ¥/m^3

Direct Cost of Work Item = A+B+C =		10082.60	¥/m^3
Overhead Cost:	0%	0.00	¥/m^3
Profit Cost:	0%	0.00	¥/m^3
Total :		10082.60	¥/m^3
VAT	0%	0	¥/m^3
Total unit cost:		10082.60	¥/m^3

Notes:

UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision

* Inclusive of transporting, loading and unloading, handling, etc.

** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.

Appendix C-5: Granular Compacted Filling Rate Analysis

3.0 FILLING

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project: Trench Backfilling Materials Life Cycle Cost (LCC)
Work Item: (3.3) Granular Compacted fill
Targeted Output Quantity: 1 m^3
Result: 18414.27 ¥/m^3

Material Cost (1:01)					**Labor Cost (1:02)**						**Equipment Cost (1:03)**				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hourly Cost
Quarry gravel	kg	175	5.50	962.50	Site Supervisor	1	0.5	0.08	5813	232.52	Backhoe Loader with fuel	1	0.06	7000	420
Quarry sand	kg	2577	6.50	16750.50	Daily Laborer	1	1	0.015	3250	48.75					
Total (1:01)				5500		Total (1:02)				1957.43	Total (1:03)				2625.17

A= Materials Unit Cost 17713.00 ¥/m^3

B= Manpower Unit Cost 281.27 ¥/m^3

C= Equipment Unit Cost 420 ¥/m^3

Direct Cost of Work Item = A+B+C = 18414.27 ¥/m^3

Overhead Cost:	0%	0.00	¥/m^3
Profit Cost:	0%	0.00	¥/m^3
Total :		18414.27	¥/m^3
VAT	0%	0	¥/m^3
Total unit cost:		18414.27	¥/m^3

Notes:
UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision
* Inclusive of transporting, loading and unloading, handling, etc.
** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.

Appendix C-6: Granular Compacted Compaction Analysis Rate

4.0 COMPACTION

ANALYSIS SHEET FOR DIRECT & INDIRECT COSTS

Project:	Trench Backfilling Materials Life Cycle Cost (LCC)		
Work Item: (4.1)	Granular Compacted fill		
Targeted Output Quantity:	1 m^3	Result:	590.31 ¥/m^3

Material Cost (1:01)					**Labor Cost (1:02)**						**Equipment Cost (1:03)**				
Type of Material	Unit	Qty*	Rate	Cost per Unit	Labor by Trade	No.	UF	Labour Output (hr/m^3)	Indexed hourly cost**	Hourly cost	Type of Equipment	No.	Equipment Output (hr/m^3)	Hourly Rental	Hourly Cost
					Site Supervisor	1	0.5	0.08	5813	232.52	Vibrating Tamper with fuel	1	0.08	400	32
					Daily Laborer	1	1	0.015	3250	48.75					
					Compactor Operator	1	1	0.08	3463	277.04					
	Total (1:01)			0.00		Total (1:02)				558.31		Total (1:03)			32

A= Materials Unit Cost	0.00	¥/m^3	B= Manpower Unit Cost	558.31	¥/m^3	C= Equipment Unit Cost	32 ¥/m^3

Direct Cost of Work Item = A+B+C =		590.31	¥/m^3
Overhead Cost:	0%	0.00	¥/m^3
Profit Cost:	0%	0.00	¥/m^3
Total :		590.31	¥/m^3
VAT	0%	0	¥/m^3
Total unit cost:		590.31	¥/m^3

Notes:

UF: Utilization Factor (UF) = 1/ the # of crew or people under supervision

* Inclusive of transporting, loading and unloading, handling, etc.

** Inclusive of benefits, travel subsides, and cost of overtime related to targeted output.