Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Structural Engineering

Eline Sjølie Osmundsen

Working towards sustainable building practice in Nepal by reducing the utilization of cement

In collaboration with Engineers Without Borders

Master's thesis in Department of Structural Engineering
Supervisor: Arne Mathias Selberg
June 2022

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In collaboration with Engineers Without Borders

Veien mot en bærekraftig byggepraksis i Nepal ved å redusere bruken av sement
I samarbeid med Ingeniører Uten Grenser

BY:

Eline Sjølie Osmundsen

SUMMARY:

The development in Nepal has moved in the right direction throughout the last decades, and several improvements have taken place in the construction industry. However, the country is still in need of new housing, public buildings, and upgraded infrastructure. Especially the demand of housing units increased drastically after the earthquake in 2015, where more than 600 000 houses were destroyed. Modern materials like concrete is replacing traditional materials. The cement production is estimated to double from 2020 to 2025. The increased use of cement is unfortunate for the sustainable development, and Nepal is already one of the countries disproportionately affected by climate change.

In collaboration with the Samaj project and the Engineers without Borders the current building practices and measures improving the present situation in terms of reducing the amount of cement utilized have been examined. Hopefully it will be possible to find alternatives that can fulfil the requirements to the materials and at the same time leave smaller CO_2 footprint. In addition, benefits from low cost, and having a positive social impact in the country are positive gains.

In this project, two alternatives have been investigated by using three different research strategies: Literature review, experimental tests and field study. The first alternative investigated is substituting parts of the cement with clay, which is a raw material distributed all over Nepal. The second alternative being investigated was the sustainability of earth-based materials to replace concrete. From the investigations done, it is possible to conclude that substituting parts of the cement with calcinated clay is possible. However, unheated clay is proven to be unsuitable to use as a replacement for cement. The research also makes it possible to conclude that earth-based materials are suitable to use instead of concrete in some cases. Still, not all, and for usage in many constructions, concrete seems to be the only acceptable option.

RESPONSIBLE TEACHER: Arne Mathias Selberg

SUPERVISOR: Arne Mathias Selberg

CARRIED OUT AT: Department of Structural Engineering

Abstract

The development in Nepal has moved in the right direction throughout the last decades, and several improvements have taken place in the construction industry. However, the country is still in need of new housing, public buildings, and new infrastructure. Especially the demand of housing units has increased drastically after the earthquake in 2015, where more than 600 000 houses were destroyed. This situation has led to large investments in the cement production. Modern material like concrete is replacing traditional materials, and the cement production is estimated to double from 2020 to 2025. The increased use of cement is unfortunate for the sustainable development, and Nepal is already one of the countries disproportionately affected by climate change.

In collaboration with the Samaj project and the *Engineers Without Borders* the current building practices and measures improving the present situation in terms of reducing the amount of cement used in the construction industry have been examined. Hopefully it will be possible to find alternatives that can fulfil the demand construction methods and at the same time leave a smaller CO_2 footprint, being of low cost, and having a positive social effect in the country.

In this project, two alternatives have been investigated by using three different research strategies. First, a literature review was conducted aiming at getting an overview of various alternatives. Then concrete containing unheated clay was tested in the lab to evaluate its suitability to replace cement. Last, a field study was conducted, in order to get valuable insight into the construction industry and the current situation, the local preferences, and the challenges connected to the shortage in public buildings and housing units.

The first alternative investigated is substituting parts of the cement with clay, which is a raw material distributed all over Nepal. The easy access in combination with the low cost makes it a favorable option from a sustainable development perspective. Concrete with unheated clay was tested in the lab at NTNU. The test results show that the strength in the concrete decreases drastically when increasing the content of the unheated clay. The results comply with the information found in the literature, and it seems adequate to conclude that this is not a suitable option. By thermal treatment, the clay mineral crystal structure is destroyed and transformed into a very reactive structure. As a result, the active phase increases, making it more pozzolanic. Evidence concerning calcinated clay shows that it is possible to obtain the same strength as when using OPC, and the durability is often improved. Calcination can be done by using the same equipment as used in cement production. Considering that Nepal only utilizes half of the capacity at the cement factories, and in addition having access to the raw material and a place to calcinate the clay, make this option worth looking further into.

The second alternative being investigated was the suitability of earth-based materials to replace concrete. All in all, earth-based materials seem to be an equally good alternative as concrete in many constructions. Especially CSEB seems to be an acceptable option being at low cost, and the CO2 emission is reduced compared to using concrete and burned bricks. In addition, the material contributes to local business and gives locals, both males and females, work possibilities in their hometowns. However, when the size of the building exceeds 2,5 stories, it is not possible to obtain the given requirements when using rammed earth or CSEB. Therefore, concrete cannot be replaced in these situations and in many cases, concrete still is the best option.

Sammendrag

Utviklingen i Nepal har vært positiv gjennom de siste tiårene, og flere forbedringer har funnet sted i byggebransjen. Til tross for dette er det fortsatt er stort behov for nye boenheter, offentlige bygg og forbedret infrastruktur. Særlig etter jordskjelvet i 2015 økte behovet for boenheter over natten som følge av at over 600 000 bygninger ble ødelagt. Moderne materialer som betong tar over for tradisjonelle materialer, og det er estimert at sement produksjonen kommer til å dobles fra 2020 til 2025. Med tanke på bærekraftig utvikling er den økende bruken av sement uheldig, særlig med tanke på at Nepal allerede til tross for landets lave klimagass utslipp, er de en av landene som er svært påvirket av klimaendringene.

I samarbeid med *Samaj prosjektet* og *Ingeniører uten Grenser* er det sett på om det er mulig å gjøre dagens bygge praksis mer bærekraftig ved å redusere bruken av sement. Forhåpentligvis er det mulig å finne alternative løsninger til betong som har et lavere CO2 utslipp, lave kostander og positiv effekt for lokalbefolkningen. Det ble bestemt at to alternativer skulle vurderes. I dette prosjektet er det sett på muligheten for å erstatte deler av sementen med leire og benytte jordbaserte materialer istedenfor betong.

Tre forskjellige metoder er benyttete i prosjektet. Et litteraturstudium er gjennomført for å få en oversikt over relevant informasjon for å svare på forskningsspørsmålene. Deretter ble utvalgte tester gjennomført på NTNU sin betong lab for å vurdere hvordan ubehandlet leire påvirket egenskapene, spesielt trykkfastheten til betongen. Til slutt ble et feltarbeid gjennomført i Katmandudalen for å få innsikt i dagens situasjon, hvordan bygge bransjen fungerer, de lokales preferanser og utfordringer knyttet til mangel på bygg og boenheter.

Først ble det undersøkt om leire, et lett tilgjengelig råmaterial i store deler av Nepal, er egnet til å erstatte deler av sementen. Dette i kombinasjon med lave kostander tilknyttet bruk av materialet gjør det til et alternativ som kan bidra til en bærekraftig utvikling. Betongen tilsatt ubehandlet leire testet i laben viser imidlertid at økende innhold av leire resulterer i at fastheten synker betraktelig. Dette samsvarer med funn i litteratur, og det konkluderes derfor med at ubehandlet leire ikke egner seg til å erstatte deler av sementen. Dersom leiren kalsineres, blir den mer reaktiv, og leiren kan fungere godt som en pozzolan. Tidligere casestudier viser at det er mulig å oppnå samme styrke som ved bruk av bare OPC og i mange tilfeller forbedres bestandigheten. I tillegg har Nepal god kapasitet på de eksisterende sementfabrikkene, og har dermed allerede det nødvendige utstyret til kalsineringsprosessen. Bruk av kalsinert leire er derfor et alternativ det er verdt å se videre på.

Det ble også undersøkt om de jordbaserte materialene *rammed earth* og *CSEB* er egnet til å erstatte betong. For mange typer konstruksjoner vil dette være et godt alternativ, og særlig CSEB som både er et lavkostlands materiale, enkelt å bygge med, gir muligheter for arbeid til lokalbefolkningen og har et lavere CO2 utslipp sammenliknet med betong og murstein. Rammed earth er også er godt materiale, men virker å ha et noe mindre bruksområde og er vesentlig dyrere enn CSEB. Likevel er betong er materiale som har gitt mye muligheter i landet, og det er ikke alle bygg som kan erstattes med de jordbaserte materialene. Betong vil derfor i noen tilfeller, spesielt når bygget har mer enn 2,5 etasje, fortsatt være det beste alternativet.

Preface

The master thesis is written in collaboration with *Engineers Without Borders Norway* and *the Samaj project*. It concludes the two-year master's degree in civil- and environmental engineering at the Department of Structural Engineering at the Norwegian University of Science and Technology.

This thesis has allowed me to combine an aid-oriented project and explore a new field, as material technology has not been part of my study program until now. In addition, I have utilized and adapted the knowledge I have obtained during my bachelor's degree and my two years at NTNU. The last semester has consisted of acquiring new knowledge, and the learning curve has been steep. However, the covid-19 situation has led to several undesirable events, and the semester has occasionally been characterized by a lot of changes, delays and uncertainties. Unfortunately, the field work that was supposed to be carried out for four weeks in urban and rural areas in Nepal was replaced with one week in Kathmandu. Thus, the clay to be tested in the lab ended up being from Dødensdal in Trondheim and not from Mustang, Nepal. Nevertheless, I could not have found a more rewarding and appropriate project to end the master's program.

This project would not have been possible without the assistance of many people, and an appreciation is given to some of the people that the task would not have been possible to complete without their assistance.

First, I would like to thank the ones working on *the Samaj Project*, with special thanks to; Martina Keitsch, professor at the Department of design, for giving me the opportunity to carry out this project by arranging parts of my field trip and connection to relevant informants; Sangeeta Singh, Professor of Urban Planning and Deputy Director of Centre for Disaster Studies, for providing information about the construction industry and arranging meetings with locals and planning visits to construction sites. RM Pandey, architect, for providing information throughout the semester about rammed earth and taking us to a rammed earth construction site in Nepal.

Secondly, I would like to thank the entire *Engineers Without Borders Norway* team, and special thanks to Elise Skattum, who has guided me and followed up with all the practicalities. In addition, my mentor Magne Gravås, section manager at Contigas construction department in Oslo, has helped with academic questions throughout the semester and accompanied me during the field work in Nepal.

Last, I would like to thank Arne Mathias Selberg, my supervisor at NTNU, for giving me the opportunity to carry out this project and guiding me throughout the entire semester.

Trondheim,
June 09 2022

Eline S. Osmundsen

Eline Sjølie Osmundsen

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List of Abbreviations

Notation/ abbreviations	**Full name and/or chemical formula**
CSEB	Compressed stabilized earth blocks
FDI	Foreign direct investment
NBC	Nepali building codes
OPC	Ordinary Portland cement
SCM	Supplementary cementitious material
RC	Reinforced concrete
w/cm	Water to cementitious material ratio
Kaolinite	$Al_2Si_2O_5(OH)_4$
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H2O)]$
Montmorillonite	(Na,Ca)0,3(Al,Mg)2Si4O10(OH)2 • n(H_2O)
Metakaolin	$Al_2Si_2O_5$, Aluminum oxide, alumina
A	Al_2O_3 , Calcium oxide
C	CaO, Ferrous Iron oxide
F	Fe_2O_3, Ferrous Iron oxide
H	H_2O , Water
K	K_2O , Potassium oxide
M	MgO , Magnesium oxide
N	Na_2O , Sodium oxide
S	SiO_2 , Silicon dioxide, silica
T	TiO_2 , Titanium oxide
f	FeO, Ferric Iron oxide
$\underline{c}$	CO_3 , Carbon dioxide
$\underline{s}$	SO_3 , Sulfur trioxide
C_3S	Ca_3SiO_5 , Alite
C_2S	Ca_2SiO_4 , Belite
C_3A	$Ca_3Al_2O_4$, Aluminate
$C_2(AF)$	$Ca_2(Al_xFe_{1-x})_2O_5$, Ferrite
$C\underline{s}H_2$	$CaSO_4 \cdot 2\ H_2O$, Gypsum

The chemical formulas are based on ref [1], [2].

1 Introduction

1.1 Background

Most climate researchers agree that climate is changing due to greenhouse gas emission caused by human activity [3]. Nepal is one of the countries disproportionately affected by climate change, especially considering that the country is one of the least contributors to the emissions of greenhouse gases [4]. The 2030 Agenda for Sustainable Development is a global plan with the aim *"peace and prosperity for all the people on the planet".* The 17 sustainable development goals are an important and a central part of the plan. UN recognizes that ending war, poverty and other deprivations must go hand-in-hand with strategies for improving health and education, reducing inequality, and working towards economic independence and growth. All this while working against reducing the climate changes and preserve the planet. To summarize it can be said that the world need to work towards sustainable development which UN defines as [5]:

> *"Meeting the needs of the present without compromising the ability of future generations to meet their own needs."*

In order to achieve the sustainable development goal action is required by all countries, developed and developing, in a global partnership [6]. At the same time developing countries, Nepal included, are in need of new housing, public buildings and new Infrastructure. This is the cause of an substantial increased cement production in the country. Traditional materials are being replaced by modern materials like concrete, and the cement production is estimated to double from 2020 to 2025 [7]. Nevertheless, Nepal is one of the countries that has committed itself to working towards achieving these goals [8]. Even though Nepal is one of the least contributors to the emissions of greenhouse gasses today the increased use of cement has an unfortunate effect considering sustainable development in the country.

The Samaj project and the *Engineers without Borders* organization have therefore expressed the need to look into the current construction practices in order to examine specific measures that may contribute to improvement of the present situation. It has been desirable that alternatives for reducing the use of concrete should be considered, in particular reducing the amount of cement used in the construction industry. Finding solutions where materials that can fulfil the demand for new constructions and at the same time leave smaller CO_2 footprint, low cost and positive social effect are therefore of interest. It is important to clarify and increase knowledge about alternative materials as this is decisive for changing of the day building practice.

One alternative is to use earth based materials, and several alternatives exist within this category. Rammed earth has in the latest years regained popularity in several countries as a natural and environmentally friendly material. A previous project in collaboration with *the Samaj project* build an apple storage with great success in Mustang in the mountain area in Nepal, using rammed earth based on local soils. Another alternative, which is quite similar to rammed earth is compressed stabilized earth blocks, herby referred to as CSEB. This is a relatively new building technique based on traditional building methods. Each alternative seems to be good option that could replace some concrete structures and will, therefore, be closer investigated in this project.

In the cases where no other adequate alternative exist for replacing the concrete structures, the use of supplementary cementitious materials, herby referred to as SCM, seems to be a promising option. One alternative that in the latest year have been examined is the use of clay as a SCM. Despite the easy access to clay in Nepal it is not widely used, and there are almost no existing studies concerning the use of clay as a SCM in the country. However, several countries have in the latest years conducted studies on local clays as SCMs.

1.2 Goal

The goal of this project is to investigate and evaluate different alternatives to reduce the use of cement in the building industry contributing towards a sustainable future. Based on the aim of the project the two research questions were formulated.

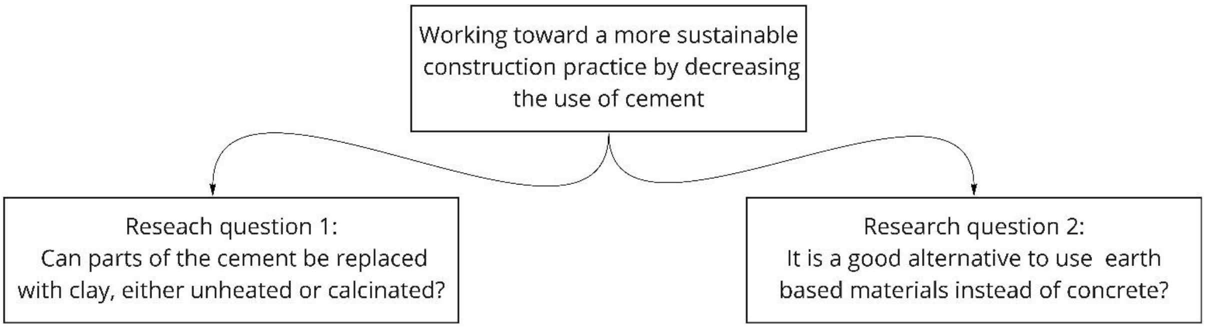

Figure 1-1 Goal of the thesis

Some sub-objectives are formulated in order to achieve the overall goal and answer the research questions. The following sub-objectives contribute working towards research question 1:

1. Acquire information about the structure and properties of cement.
2. Acquire knowledge about the structure and properties of clay and clay minerals.
3. Investigate how calcination can improve the pozzolanic activity in clays.

Further, to answer research question 2 the following sub objectives were formulated:

4. Acquire information about the materials, components, composition and properties.
5. Investigate if the materials contribute to preservation of the local building traditions and promotion of more local skilled expertise, and local business.
6. Investigate the environmental impact of the different materials.
7. Acquire information about how the different materials results in an economically feasible building practice.
8. Get an overview of the costs connected to the different materials and examine if they can provide an economic feasible building practice.

1.3 Scope and delimitations

The goal is to reduce the amount of cement used in the construction industry working towards a more sustainable building practice, which is based on three fundamental pillars: economic, environmental, and social [5]. However, before this can be discussed, it needs to be clarified if the alternative is suitable for the construction industry in Nepal.

First, replacing cement with clay is investigated. To understand the suitability of the clay as a pozzolan, its structure, chemical composition, and mineralogy are briefly examined. Then both unheated and calcinated clay aptness are investigated based on pozzolanic behavior and ability of the concrete to keep its strength, durability, and workability when the clay is added. In addition, it is essential to evaluate if it is possible to produce the calcinated clay in the country and the soil availability.

Secondly, using earth-based materials, rammed earth and CSEB, instead of concrete is investigated. The composition and properties of the material are overviewed, and the construction methods and how details of the building with the materials are looked into. In this case, the strength, durability, and workability of the materials are the foundation of the consideration. However, when introducing a different material and not just modifying an existing one, other aspects must be considered. The preferences of the locals and the availability of the raw materials are decisive.

The project covers two very different alternatives in order to achieve the goal. However, this makes the theme of the project broad, and thereby not possible to cover all aspects. The objective is to give an overview of the two alternatives, and examine if the options are worth looking closer into in the future.

1.4 Report structure

The project consists of four main chapters and the introduction, discussion, and conclusion. Some places, entire paragraphs are based on the same source, then the source is given in the first sentence. In Chapter 6. Discussion, references are not given, but the discussion is based on the information provided in one of the previous chapters.

In chapter 2, the literature review results are presented, i.e., existing information regarding the research questions and necessary background information. The chapter is divided into four main parts:

- Information about the country: background information, an overview of today's situation and essential factors that are the key to evaluating if any of the alternatives is possible to implement.
- Overview of concrete as a building material focused on using the material in Nepal. In addition, a more detailed description of cement and the hydration process is given to understand better if clay can substitute parts of the cement.
- Information about clay, clay mineral and its structure, and how the material can be used as a SCM, and an overview of relevant studies done on the use of unheated clay or calcinated clay to replace parts of the cement.
- Overview of earth-based materials focused on RE and CSEB. The building techniques and material components, compositions, and properties are described.

Chapter 3 describes the different methodologies used in the project. This chapter aims to introduce the research strategy applied to the project and the assumptions underpinning the research.

Chapter 4 presents the results of the experimental tests: the slump test, compressive strength, and bending strength, as well as a short review of the additional test.

In chapter 5, the results from the field work are presented. The information is based on observations, conversations, and interviews conducted. It gives valuable insight into the construction industry and the situation of the day, the locals' preferences, and the challenging connection to the shortage in public buildings and housing units.

2 Theory

2.1 Background information about Nepal

2.1.1 Geographical information

Nepal is located in Southern Asia between China and India. It has a total area of 147 181 km^2 [9], which is a bit smaller than half the size of Norway. The population counts 30 424 878 (July 2021), approximately 5 000 000 lives in Kathmandu Valley, and the yearly population growth is 1,8 % (2014 est.) [10]. Nepal is a developing country and approximately 25 % of the population lives below the poverty line [11].

The topography and the climate condition vary significantly within the country, mainly due to big elevation differences [12, p. 2]. There are several different definitions and ways to divide the ecological zones in Nepal. According to the Demographic and Health Survey from 2011 the topography can be divided into three distinct ecological zones as shown in Figure 2-1: mountain, hill, and terai [12, p. 1]. Kathmandu Valley consists of Kathmandu, Bhaktapur, and Lalitpur located in the hill zone in the central region of the country.

Figure 2-1 Map of Nepal, and where Katmandu Valley is located [12, p. xxiv].

The climate varies from subtropical in the lower parts of the country to a colder climate with snow and glacier the entire year in the mountains, where big parts of the Himalayas are located [12]. Kathmandu Valley is situated in the temperate climate zone and has the highest average temperature in June of 20,5 degree Celsius and the lowest temperature in January of 9,2 degrees Celsius [13]. While the areas closer to China experience colder temperature and the areas towards India have higher temperature. Monson season occurs from June to August, and heavy rainfalls occur almost daily in this period, which in many areas affect the construction work.

Nepal is located in one of the most seismic active zones in the world, making the country prone to earthquakes, avalanches, landslides and floods [14], [15]. Throughout times, the country has been hit by several earthquakes. Spring 2015 big parts of Nepal, see Figure 2-2, were hit by two earthquakes with magnitude 7,8 and 7,4 [15], [16]. Leading to major damages and making 3 000 000 people homeless [11]. All types of structures were affected suffering extensive damages including partial and complete collapse [17]. Also, the earthquakes in 2015 trigged avalanches on Mount Everest and landslides that destroyed both rural villages and densely populated areas [14].

Several field studies have been conducted after the earthquakes, and cause- and type of failure have been identified [17], [18], [19],[20]. One major problem is that, even though it is well known that the area is prone to earthquakes, this is not always taken into account. Several constructions that failed had been built without being designed properly, and seismic forces had not been taken into account. Most of the buildings that were destroyed had not been constructed by engineers, and several shortcuts had been made during the construction. However also well designed buildings got damages during the earthquake, and many well designed tall buildings had significant nonstructural damages. It is foreseen that more earthquakes will hit Nepal in the future, which require building design that can guarantee better quality and less damages in the future.

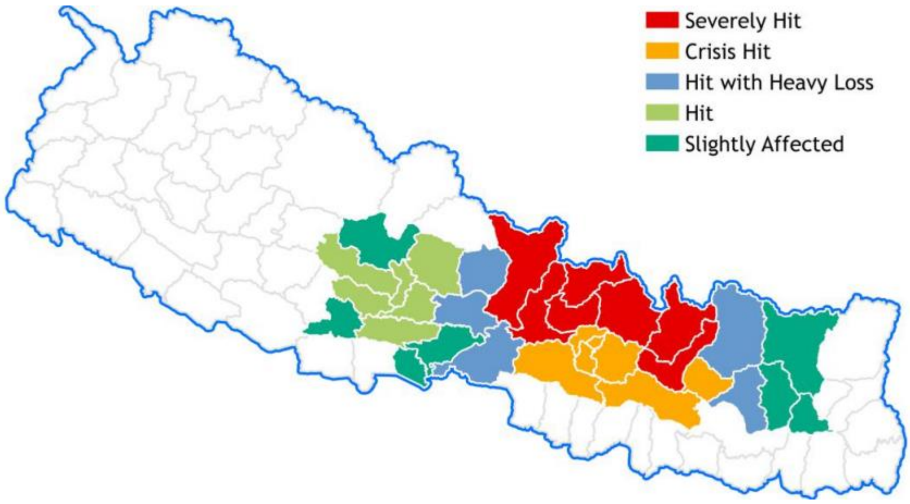

Figure 2-2 Areas hit by the earthquake in 2015 [16]

Other seismic activities are also affecting the country. Melting of glacier and heavy rainfalls lead to floading almost every year in parts of Nepal [15]. Cyclones in the Bay of Bengal can cause heavy rain and snow in the Himalayas, increasing the risk of landslides and avalanches. It is often several landslides in the monsoon season, and the roads are dangerous. These type of natural disaster often have serious consequences. Human lives are lost, several are injured and many loose their houses.

The country is landlocked, which makes export and import more difficult and expensive than for their coastal neighbors [21]. The infrastructure in Nepal is limited, and few independent nations of comparable size have as few vehicles and small transport network [11]. This makes it challenging to transport necessary materials into and around the country. The primary means of transportation have been the network of footpaths, which have evolved into main trade routes. Construction of new roads has been an ongoing process since the 1970s with aid from India, China, Great Britain, and the United States. The road-transport facilities in Nepal are supplemented by only a few railways and air-transport links.

2.1.2 History and architecture

Nepal has a diverse culture based on centuries of traditions [22]. This is rooted in the ethnic, tribal and social groups' diversity and expresses itself in everything from language, literature, religion, culture and architecture [22], [23]. The official language is Nepali, but 143 different languages were reported as mother tongue in 2011 [9].

Hinduism is the most widespread religion, followed by Buddhism, but several other religions are also widespread. The wide variety of religions has influenced the architecture in the country [23]. As a result of both Buddhism and Hinduism developed all over Asia, both religions prospered in Nepal influencing the architectural expression. Especially the time period between 1500 AD- 1800 AD was characterized by an architectural development resulting in what UNESCO describes as [23]:

"A powerful artistic and architectural fusion"

The country has a rich cultural heritage and a lot of traditions. There are several areas, monuments and buildings listed in the UNESCO world heritage list, most of them located in Kathmandu Valley [24]. These areas and construction display the full range of historic and artistic achievements and define the unique cultural traditions of the Newars. The structures exhibit exceptional craftsmanship, and they are mainly built using brick, stone, timber and bronze. [23]. Some structures from Kathmandu Valley are illustrated in Figure 2-3.

Figure 2-3 The picture to the left is taken at Patan Square, one of the places listed in UNESCOs culture heritage list. Picture to the right illustrate some of the buildings still standing after the earthquake. (Picture from field study)

In addition to being the home for big parts of the cultural heritage in the world, Kathmandu Valley is the most urbanized area in Nepal [12, p. 1], and several modern buildings can be observed. The first reinforced concrete structure dates back to 1940, and the building was a part of the Trichandra College [25]. In that time, reinforced concrete was considered an alien practice introduced by the Ranas, a Chhetri dynasty in Nepal. Lack of technical skills, human labor and limited access to building materials the construction method were rarely used in the following years. First, when the country gradually opened up for international collaboration the construction method became the most popular method for larger-scale projects. Today reinforced concrete seems to be most preferred by the Nepalis for larger-scale and smaller-scale projects, and it has become a widely used construction method [17], [25]. In Figure 2-4 some concrete and brick structures are presented.

Figure 2-4 To the left, a new school building where concrete and red bricks are combined. Picture to the right shows a concrete building in Kirtipur. The first floor is used as a store, which is a typical set up for buildings in Nepal. (Pictures from field study)

In the last few decades, urban development has grown in an unprecedented trend, and the Kathmandu Valley Town Development Committee predicted in 2000 that 435 662 housing units would be needed by 2021. Almost all of the new buildings in the urban areas are reinforced concrete and masonry structures, which have become the most popular and accepted construction technique in the valley and the rest of the country [25].

2.1.3 Natural resources

Despite of the relatively easy access to natural resources, Nepal is one of the poorest countries in the world [11]. The utilization of local resources is not utilized to its full potential. The industry is poorly developed, and the country is dependent on aid from other countries.

The largest energy source today is forestry. Approximately 1/4 of Nepal is covered by forest [7]. However, the area covered with forest has almost been halved in a few decades because of the use of wood as fuel, and it is no longer easy to get hold of the material.

Soil is a nature resource that is available in big parts of Nepal, making it possible to build with local materials. However, the quality varies depending on the location in the county, and the soil needs to be tested when used in larger scale structures [26]. The soil consists of varying proportions of four types of material; gravel, sand, silt and clay [26]. It is a complex material, and several factors influence the properties of the soil [27], [28], which is further described in Chapter 2.4.2.

The biggest challenge when it comes to natural recourses used in concrete, is the availability of fine aggregates. Places where sand can be extracted, suitable for use in concrete, are limited. The high demand of sand in the construction industry leads to big economic value of sand. This has led to many people being involved with sand excavation, both legal and illegal, and the excavation of sand is today out of control. Especially the illegal mining activities will in the long term affect people and the environment. Despite this, some point out that for the time being these activities provide good opportunities to many people living hand to mouth [29].

2.1.4 Building typologies

Throughout Nepal a combination of traditional and modern buildings can be observed. In 2011 the country material distribution were as illustrated in Figure 2-5. Already then RC buildings were popular, especially in urban areas [17]. Older structures in Nepal are mostly made of mud and wood, which until the last decades have been the most common building materials because of the occurrence of good soil and abundant forest resources [30].

Since then, the percentage of RC buildings has increased every year, particularly after the earthquake in 2015, and today almost all new structures in the urban areas are built using RC and bricks. In 2016 20% of the buildings in urban and suburbs consisted of RC constructions, and the majority is non- engineered to pre-engineered constructions such as owner built houses [18, p. 2]. In the rural areas more traditional materials are still most common, but also here cement based materials are utilized. Also use of wood and masonry with mud mortar have decreased.

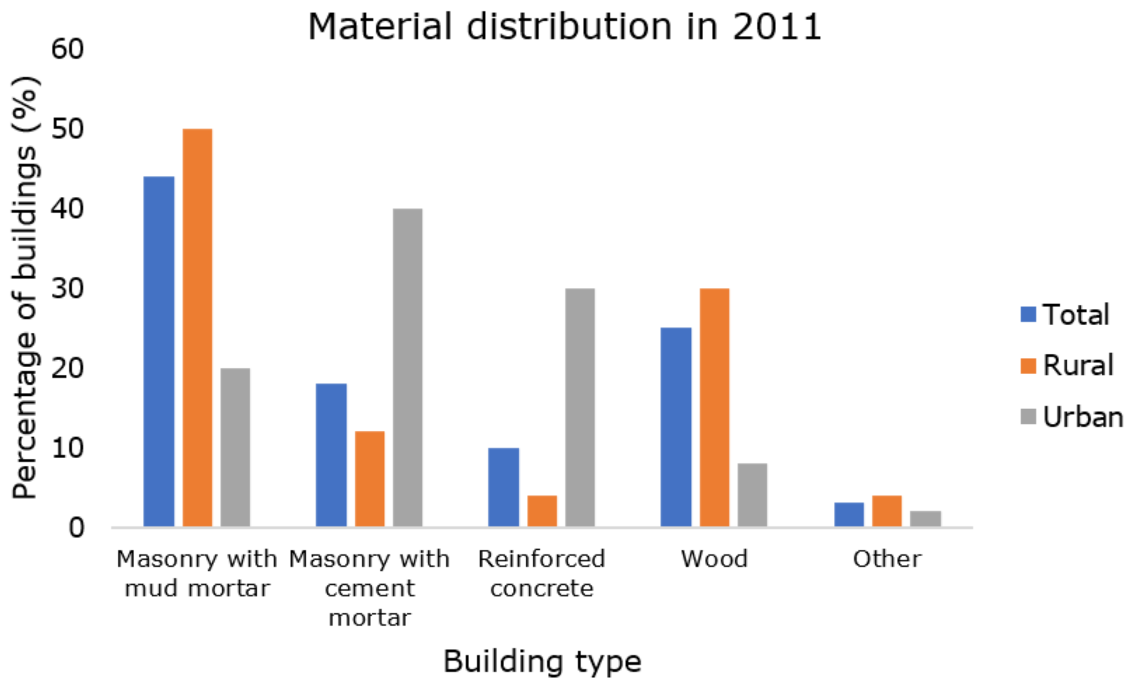

Figure 2-5 Construction materials in Nepal based on ref [17].

The raw materials used depend on the location and building age [17]. Especially older buildings constructed before the existence of design codes are categorized by poor quality, many of them destroyed in the earthquake in 2015. Newer concrete buildings have a higher quality, and the main construction issue is often related to the existence of soft stories. It is common to have an opening on the road-facing side, used for retail shops, which results in lower stiffness and strength with respect to upper floors.

Data on house size compiled by the HRRP, The Housing Recovery and Reconstruction Platform, provides the following information, as presented in Figure 2-6, on how house size has changed in earthquake affected areas [16]. As illustrated, the size of new houses has been reduced and almost 90 % of new houses is smaller than 50 m2.

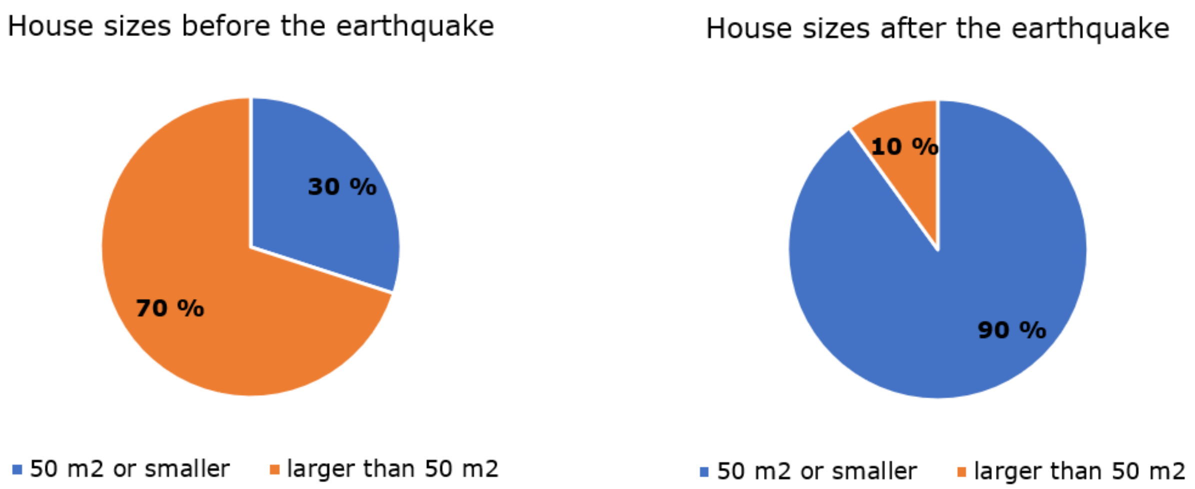

Figure 2-6 Size of houses before and after the earthquake, complied by HRRP April 2019. Figure based on ref [16]

2.1.5 Locals' preferences and socioeconomic impact of concrete

Understanding the locals' preferences is essential when planning future housing [25]. E. Shrestha [25] conducted a survey where 50 Nepali were asked several questions about the usage of concrete in Nepal. The participants in the study were all in the age group 25-40 years, and 91,7 % of them lived in RC houses. 62,5% preferred RC structures, while 37,5 % preferred other building practices. There are mainly three factors identified which have equal influence on the preferences of RC building practice; building design aspect, construction favorability and social aspects associated. A summary of the study and the answers are presented in Table 2-1.

Table 2-1 Table copied and adapted from Shrestha [25]. All the variables were divided into a 5-point scale, where one represented "strongly disagree" and five representing "strongly agree". Finally, the mean values of the participants' answers are given.

Factor	Grouped variables	MEAN
Factor 1 Building design aspects	RC buildings last longer	3,68
	RC buildings structurally stronger	3,62
	RC buildings aesthetically pleasing	3,68
	RC buildings are flexible with design	3,18
Factor 2 Construction favorability	RC buildings favored by resource marked	4,0
	RC buildings cheater to build	2,9
	RC buildings easier for building permits	3,02
	RC buildings easier to build	3,46
Factor 3 Social aspects associated	No knowledge of other construction practice	3,02
	RC buildings because of the trends	3,02
	RC buildings because of social status is raised	2,96
	RC buildings to be modern	3,22

In the survey, it is concluded that all three factors are equally important in determining RC buildings' preferences in practice. However, some variables stand out. RC buildings are associated with high status, this seems adequate considering big developers and wealthy people in the country often prefer the material. From the answers it also seems like durability, strength and availability are important when choosing construction method.

Shrestha points out that all three factors should be addressed to resolve what he describes as a building practice characterized by only using concrete resulting in loss of traditional building practice, adverse environmental impacts, and uncontrolled urban development in the Kathmandu valley. Further, it is concluded that other suitable forms of construction techniques should be explored for better building design, flexibility, and more conveniently favor the construction works. The public should be encouraged to adopt other forms of sustainable construction practice. Overall, it seems like the residents' perceptions regarding the use of concrete vary, and alternative materials should be explored further.

In 2021, P. Kumar Shrestha [17]. conducted a socioeconomic impact analysis about the cement production at the Economic Research Department. The study was based on a survey where 84 people participated: 14 employees and 70 locals living nearby seven of the 55 cement manufacturers in the country. Cement manufacturing accounts for 31.24 percent of the total installed capacity of the entire cement industry in the country. The participants were asked several questions, and the ones with a yes/ no answer are presented in Figure 2-7.

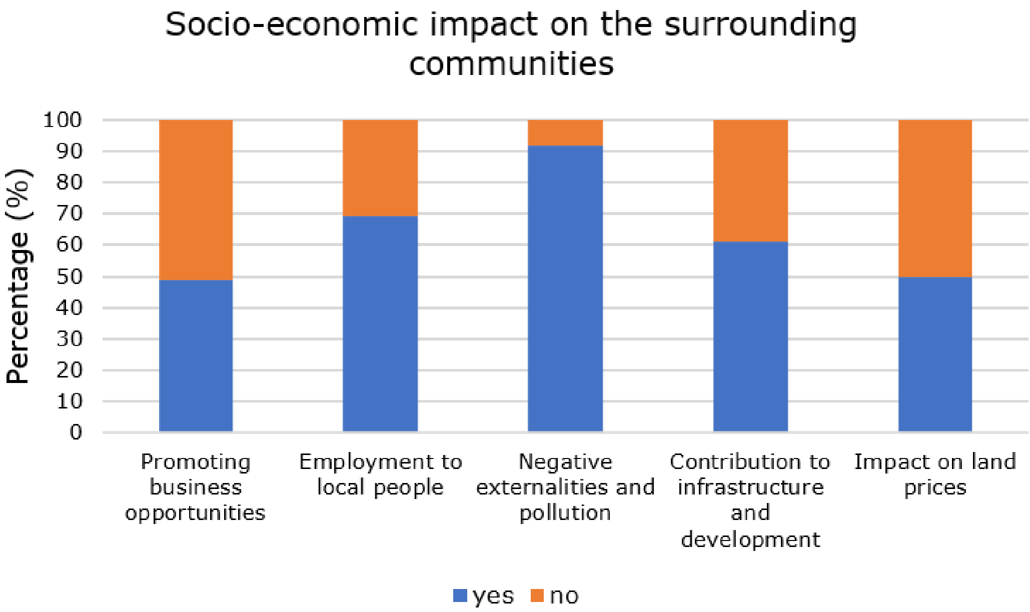

Figure 2-7 Socio- economic impact on the surrounding communities. The answer opportunities were yes/no which make the result a bit misleading. Based on ref [17].

From the survey [17], it appears that the cement industry has a beneficial influence in the country. As a result of the establishment of the cement factories, a growth in business activities like hotels, restaurants, and retailers have taken place. Then access to the road networks, schools, hospitals and vehicles have occurred in the areas where the factories were built. Government-owned cement industries have contributed to building schools and providing subsidized prices to locals. Most employees work 8 hours a day and earn more than Rs 40000 per month, which is higher than the average salary in the country, and furthermore they receive benefits like bonuses, provident funds and insurance.

The cement industry has, however, also negative consequences, and the result given in Figure 2-1, may be misleading. For example, even though around 60-70 % answered that the cement production has created employment opportunities for the locals, it does not specify anything about how many locals working in the factories. The results can therefore give a slightly incorrect impression, and in reality, less than 10 percent of the total employees are locals [17]. It seems like the industry prefers to avoid local people due to lack of skills and avoid unionism. In addition, almost all employees are male, and the cement industries do not give work to many female citizens. Another increasing problem is the air- and sound pollution influencing daily activities due to the cement industries' operations.

2.1.6 Cement industry in Nepal

During the last few years, the clinker and cement production have increased, especially following the post-earthquake reconstruction in the Country. Currently, 55 cement industries are operational in Nepal [31].

- 3 Foreign direct investment based, herby referred to as FDI.
- 2 government-owned
- 50 locally and privately owned.

See Table 2-2 for information about amounts concerning the cement industry in Nepal. Due to increase in domestic production, cement import has declined. However, new cement industries have been established in FDI. This has created an optimistic scenario for the country to move further in the path of self-sufficiency in this production.

Table 2-2 Cement production (2020) adapted from table 8 [31].

Description	Quantity (Million Metric ton)
Annual installed capacity	15,00
Annual actual production	7,49
Domestic consumption demand	9,05
Export	0,00
Import	1,56

The country aims to be self- sufficient when it comes to the cement production, and the domestic production has increased, and new cement industries have been established and planned for in the future [31]. The import of cement has therefore declined. However, still 1,56 million metric tons of cement were imported from India in 2020, although annual production capacity in the country was not fully utilized. This is mainly because the largest scale projects in Nepal often import cement from India due to issues of certification, quality consistency and ability for bulk supply related to domestic cement suppliers.

The annual actual production is half the amount of the annual installed capacity, and establishment of cement factories are planned to take place in the future. If calcination of clay becomes an adequate option, the existing cements factories can be used in the production of calcinated clay, therefore little capital intensive is required [32].

2.1.7 Nepal building codes

The NBC are developed by The Department of Urban Development and Building Construction under the Ministry of Physical Planning and Works [33]. Some of the NBC were first drafted in 1994, and others were updated in 2015. The design code for concrete structures was not published until 2006, even though the use of the material by then was already widespread in the country [17]. As a consequence of this, several buildings are built without fulfilling the requirements. Today the building codes cover mainly concrete and masonry buildings, but there is also information about other materials like steel, timber and earth-based materials. The NBC relevant for this project are:

- NBC 201: Mandatory rules of thumb reinforced concrete buildings with masonry infill
- NBC 204: Guidelines for earthquake resistant building construction: Earthen buildings
- NBC 205: Mandatory rules of thumb reinforced concrete buildings without masonry infill

For information about all types of loads, the Indian standard IS:875 is adapted. Most relevant for the type of buildings considered in this project are part 1 and 3, which cover occupancy loads and unit weight of materials and wind load, respectively.

In addition to 24 national building codes, the country has around four hundred other standards covering everything from cement production to aggregates. Aggregates conform to the requirements of the Nepal standards NS: 305-2050 (Methods of test for Aggregates for concrete) and NS: 297-2050 (Aggregate). It seems, unfortunately, as these standards are not available in English.

Ancient building techniques developed ages before the existence of building and design standards was mainly done by rules of thumb developed through years of experience. As a result, national standards have not been published for rammed earth or other earth based materials, except from earthquake resistance guidelines. However, over the past fifty years, a number of standards and national references have been published in Australia, Germany, New Zealand, Spain, the USA and Zimbabwe [27], so guidelines do exist on a worldwide basis.

2.1.8 Requirements to the material

The properties have great influence when deciding what type of material that should be used, and it depend on the raw materials and how they are combined [34], [2, Ch. 4]. The design is often determined by requirements for strength and durability. In addition, it is important that the workability is satisfied for the chosen product.

Strength is defined as the ability to resist stress without failure [34]. The strength of the material is affected by several factors, some important are [34]:

- Water content
- Aggregate size and mineralogy
- SCM
- Minerology of the components
- Admixtures
- Air-void system
- Compaction
- Degree of hydration

Designing for a durable construction is important, especially considering that at least three generations use masonry houses without any strengthening measures [18]. Durability is, in the report by Taylor et al. [34] defined as:

> *"The ability to resist weathering action, chemical attack, abrasion or any other process of deterioration and retain its original form, quality, and serviceability when exposed to the environment."*

When talking about concrete, workability includes that the concrete has mobility, stability and is compressible [35], meaning the ability to stay homogeneous, being able to float/move and being able to fill out the formwork and be proper compressed. For both the earth based materials, having several similarities with using concrete, the same factors are important.

2.2 Concrete and use of the material in Nepal

2.2.1 General information

Except for water, concrete is the most used material in the world by mass [36], [37]. The estimated yearly consumption is 30 billion tons, and the worldwide demand is ever-growing [36]. Nepal is no exception, and almost all new constructions are made of concrete [25].

Concrete is a composite material consisting of cement, aggregates and water [2]. In addition, it is common to ad admixtures. Both unreinforced and reinforced concrete are used in Nepal, but the latter is the most common. Reinforced concrete has a broader usage area and can be utilized in most types of structures. The reinforcement used in Nepal has a characteristic strength of 415 MPa. Field surveys from 2017 indicate that most reinforced concrete buildings have 3-5 floors, and the most frequent dimensions for the different construction elements are presented in Table 2-3 [17]. Unreinforced concrete can be used when the construction component is mainly loaded in compression, such as retaining walls, strip- and slab foundations, columns, and walls [38]. Unreinforced concrete is less ductile and has little tensile strength. Unless measures have been made to avoid local tensile fractures, large eccentricity should be avoided for the axial force in a cross-section to prevent cracks. It is stricter rules for the dimension when using unreinforced concrete.

Table 2-3 structural elements and frequently occurring dimensions in mm. Adapted from ref [17]

Structural element	Dimension in mm
Columns	230x230, 230x300, 300x300 (more recently)
Beams	230x320
Slabs	100-150

2.2.2 Cement

The main component in the manufacturing of Portland clinker is limestone, and it accounts for over 90 % of the raw materials [2]. In addition, limestone is mixed with minor constituents such as bauxite, quartz, gypsum and industrial waste. The clinker usually consists of 60-67% C, 17-24 % S, 4-7 % A, 1,5-5 % F, 1-5 % M, 0,5-3,5 % s and 0,2-1,5 % K+N. The major oxides are combined in the clinker producing the clinker minerals presented in Table 2-4. The production of traditional Portland cement requires heating to 1450 degrees [36]. The major oxides account for approximately 95 % of the cement [2]. In addition, some minor components are necessary to include for the practical use of Portland cement. These secondary components make up about 5 % of the cement.

Table 2-4 Major phases in OPC [2, pp. 6–3 to 6–5]

Clinker mineral	Term	Abbreviation	Wt. %
Tricalcium silicate	Alite	C_3S	55-60
Dicalcium silicate	Belite	C_2S	14-20
Tricalcium aluminate	Aluminate	C_3A	5-10
Tetracalcium aluminoferrite	Ferrite	C_4AF	6-10

Alite is the phase with the highest amount of lime, and it reacts relatively rapid with water [2]. As a result, Alite gives strength at both early and later age. Belite consists of less lime than alite, and the reaction with water is slower. It contributes significantly to long-term mechanical strength, but belite contributes little to the early age strength because of the slow reaction. Aluminate and ferrite act similarly when in contact with water, but the latter reacts much slower. Aluminate is not sulfate resistant, and the amount should be limited in sulfate resistant concrete. Ferrite is what gives concrete the dark grey color.

The major phases are reactive towards water [2]. Hydration is the chemical reaction between cement and water, giving the cement binding properties and becoming a cement paste. The hydrates contain chemically bound water w_n which is defined as [2]:

$$w_n = \frac{weigh\ loss\ between\ \ dry\ weight\ and\ igntied\ weigh}{ignited\ weight}$$

For Portland cement the chemically bounded water is proportional to the amount of reacted water. The degree of hydration is defined as [2]:

$$\alpha = \frac{cemically\ bound\ water\ at\ a\ given\ time}{chemically\ bound\ water\ at\ full\ hydration} = \frac{w_n}{w_n(\infty)} = \frac{w_n}{0{,}23}$$

The main types of hydration products are [2]:

- C-S-H: Calcium silicate hydrate
- CH: Calcium Hydroxide
- AFt and AFm phases

C-S-H is the most essential component in hydrated cement, and it is the material that gives hydrated Portland cement its strength. It is produced in the following reactions [2]:

$$2C_3S + 6H \ \rightarrow C_3S_2H_3 + 3CH$$

$$2C_2S + 4H \ \rightarrow C_3S_2H_3 + CH$$

As shown in the reactions, C_2S produces more binder than C_3S and is more efficient at complete hydration [2]. However, the C_3S gives rapid strength development and contribute to a high strength at a late age. This is very important in practice, and the content of C_3S has increased over the years.

CH is a byproduct of the reaction forming C-S-H [2]. It is a weak portion of concrete that forms within C-S-H at early ages and then in water-filled spaces at later ages. CH help keep the pore solution pH high (>13). This is important for durability (reinforcement). If CH is dissolved from lowering the pH, then the concrete will become porous.

AFt and AFm are two phases in the hydration process [2]. The most common AFt phase is ettringite which is a result of the following reaction [2]:

$$CSH_2 + C_3A + H \ \rightarrow C_3A \cdot 3CS \cdot H_{32}$$

Ettringite is responsible for some initial stiffness and strength gain [2]. It absorbs water as it grows, and there is a significant volume change. At later stage of hydration, AFt is consumed to form AFm. Monosulphate and monocarbonate are most common, produced from the reaction [2]:

$$C_3A + Aft + H \ \ \rightarrow AFm$$

When cement is added water, hydration products that glue the aggregates into concrete, are made. This is often called cement paste. The properties of the cement paste depends on the ratio between water and cementitious material [39], and it influence both strength, durability and workability. Increasing the water content concrete will increase the flow and compactability, thereby improve the workability. However, the strength and the durability decreases when the water content increases [34].

2.2.3 Aggregates

Aggregates generally comprise around 65-75% of the concrete volume and can be natural, industrial manufactured or recycled from previous construction work [2]. In Nepal natural aggregates are most common [40]. The mechanical properties of the concrete depend on the mechanical properties of the aggregates, especially when it comes to E-modulus and stiffness [39, p. 108]). Therefore, the properties have a significant influence on the total economy for the production of concrete, especially concerning the use of cement [41]. Some of the parameters that influence the properties are; material grading, particle shape, amount of free mica, type and composition of fine particles and water absorption [2].

Aggregates are often divided into coarse and fine. Particles with a size of 4,75 or smaller are defined as fine aggregates or sand, and particles of greater size than 4,75 are defined as coarse aggregates. In Nepal the ratio between the fine and coarse aggregates is 1:2, meaning that approximately 33,3 % is sand and 67,7 % is coarse aggregates [33].

The fine aggregates used in Kathmandu Valley are mostly retrieved from river terraces and riverbeds, and are mainly composed of quartz, feldspar, rock fragments and mica [29]. The average amount of mica is 18 % and 19 % for the river and terrace sand, respectively. The high amount of mica influence negatively the compressive strength and the water demands increase [7], which causes concrete with a lower strength and poor workability. The shape of the quartz grains ranges from angular to subangular. Percent fines in the river sand ranges from 0.19 to 1.24%, whereas the percentage fines in the terrace sand ranges from 0.21 to 1.08 %.

The coarse aggregates found and used in Kathmandu Valley consist of sedimentary and metamorphic rocks with the main constituent of the minerals calcite, quartz, biotite, muscovite and plagioclase [40]. The shape of the aggregates is crushed, angular and sub-angular, and the sizes vary between 4,75 mm to 40 mm. Strength tests show some variation in mechanical strength, but overall, it is defined as medium strength aggregates.

2.2.4 Admixtures

Admixtures is not an essential component but gives possibilities to utilize concrete in places that the material has previous not been used. Mainly because it makes it possible to use a broader range of ingredients in the concrete mix [42, p. 243]. Today, it is an important and increasingly widespread used component. One definition of admixtures is [2]:

> *"Material added during the mixing process of concrete in a quantity not more than 5 % by mass of the cement content of the concrete to modify the properties of the mix in the fresh and/or hardened state."*

The effect of admixtures varies depending on the amount added and the other components in the concrete. Several different admixtures exist, providing the concrete with different properties. Some common properties that can be modified or changed by adding admixtures are presented in Table 2-5 [43].

Table 2-5 Concrete properties in the fresh and hardened state can be modified using admixtures [43].

Fresh concrete	Hardened concrete
• Workability • Flow properties • Slower/ faster hardening time • Acceleration of strength development	• Final strength • Frost resistance • Density/ permeability • Reduce waste

2.2.5 Proportioning

Concrete contains approximately 7-8 different constituents, and it is not easy to predict how these components alone or combined influence the properties of concrete. The particle-matrix model attempts to create a simplified model of these relations by dividing the material into a matrix phase and a particle phase [2].

The particle phase is all components with a size of 0,125 mm or bigger [13], consisting mainly of the aggregates. This phase controls the properties of the fresh concrete. Shape, particle size distribution, void content, and aggregates packing decide how large the matrix volume will be.

The matrix phase is all components with a size smaller than 0,125 mm, such as cement, SCMs, fillers, water and admixtures [35]. The matrix is the flowable component which envelopes the solid particle phase and fills all voids between the aggregate particles. The matrix composition controls the properties in the hardened concrete. The cement paste often has lower durability and strength than the aggregates. Required compressive strength and durability of the concrete control the matrix composition.

The particle-matrix model must be current to get the desirable properties of the concrete mix. It must be flowable, have low floating shear stress, but at the same time stay tough so the particles do not get separated. Water cannot be excreted since this will result in a change in matrix properties, and water pores and water channels are formed on cast surfaces. It is also essential that separation does not occur. All these factors depend on the particle-matrix composition of the concrete [35].

Water to cement ratios is another ratio that is important when mixing concrete. The mass ratio may be the factor that has the biggest influence on the quality of the cement, and thereby also the properties of the concrete [39]. The equivalent w/cm ratio is given by the ratio [2, Ch. 7]:

$$w/cm = \frac{w}{c + k * p}$$

Hence w is the water content, c the cement content and p the active addition. The k-factor concept is a part of the equivalent w/c ratio. The k- factor is the value that produce a mass ratio equal to the w/cm ratio of a reference mix with the same properties as the one with the additions. In other literature referred to as w/cm [34]. Normally a w/cm ratio between 0,4-0,5 is optimal.

2.2.6 Material properties

According to the Nepali building code, concrete should have a minimum compressive strength of 20 N/mm² corresponding to the nominal mix M20 [17, p. 9].

Nominal mixes give the volume ratio between cement, sand and gravel, and have the following notation [40]:

$$Mxx = Mix\ to\ obtain\ cube\ compressive\ strength\ of\ xx\ N/mm^2$$

Table 2-6 shows the mixing ratios for the most used nominal mixes [40]. In practice, various grades from low to medium strength (M10-M20) are being used in Kathmandu Valley. The mixing process is often not made after any specific mix design resulting in a great variety in measured strength [17]. Especially older concrete structures, built before the design codes' existence, have a compressive strength of approximately 10-15MPa.

Table 2-6 Nominal concrete mixes [40]

Nominal Mix	Mixing ratio	Compressive strength cube test
M10	1:3:6	10 MPa
M15	1:2:4	15 MPa
20	1:1,5:3	20 MPa

Compaction is the process where entrapped air from the freshly placed material is removed and the aggregate particles are packed together to increase the density [26], [44]. Proper compaction ensures that the formwork is completely filled. For a given w/cm the strength is said to be reduced with 5 % for every 1 % air by volume added in the concrete [34]. In practice an air content of 0 % is not possible nor desired, and in a mix with low w/cm and cement content some entrained air is supposed to improve the strength of the concrete. Air voids, especially large voids increase corrosion, lead to physical damage and decreased durability of reinforced structures by increasing the chloride threshold for the corrosion initiation of steel reinforcement [34].

There are several factors that need to be considered when designing for a durable construction [34]. Concrete is a porous material with pores in hydrated cement paste, aggregates and in the interfacial transition zone. In addition, voids can occur due to deficiencies. The pores can become penetration paths for fluids and ions, which have a harmful effect on the durability of the material. Factors affecting the durability are the effect of w/cm, SCM and air-voids system on permeability.

Workability includes that the concrete has mobility, stability and is compressible [35]. Stability can be defined as the ability to retain its homogeneity through the fresh phase. Lack of stability may lead to separation of water, paste or mortar- or coarse aggregation. Mobility can be defined as the ability of the fresh material to move due to the forces acting on it. Last, compactability can be defined as the ability of fresh concrete to fill out the formwork of encapsulated air pockets during reworking. Some important factors describing a workable concrete mix are as follows [42]:

- The consistence make it possible for the mix to be transported and fill voids.
- It can be influenced by vibration and let air get out and become a compact material.
- It is being able to stay homogeneous and not segregate.

2.3 Clay as substitution for cement

2.3.1 Clay definition

The definition of clay was first formalized in 1546 [45]. Since then, the definition has been revised, new ones have been proposed, and still, an unambiguous definition does not exist [1]. In 1995 one definition was presented by the Clay Minerals Society [45]:

> "Clay is a naturally occurring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents and will harden with dried or fired."

Fine-grained definition varies, but most geologists refer to particle sizes < 2 μm for the clay mineral fraction. Plasticity refers to the ability to be molded into any shape. Clay particles have a high potential for shrink/swell and high resistance to weathering. Clay has been used as a pozzolanic material for thousands of years [46].

2.3.2 Clay minerals

Several different clay minerals with different structures and compositions exist [1]. Hence, it is common to divide clay minerals into three classes:

- Kaolin group the most common clay mineral is Kaolinite.
- Smectite group the most common clay mineral is Montmorillonite.
- Illite group the most common clay mineral is Illite.

They all consist of the same two fundamental building blocks, even though the three groups are very different [47], [48]. The first building block is a tetrahedral sheet composed of several tetrahedrons. Each tetrahedron comes from bonding one cation, T in the figure, to four oxygen atoms, as illustrated to the left in Figure 2-8. Si^{4+}, Al^{3+} and Fe^{3+} are common tetrahedral cations. Then, the shearing of three oxygen atoms links the tetrahedron to form an infinite two-dimensional hexagonal pattern along with the a and b crystallographic directions, as illustrated in Figure 2-8.

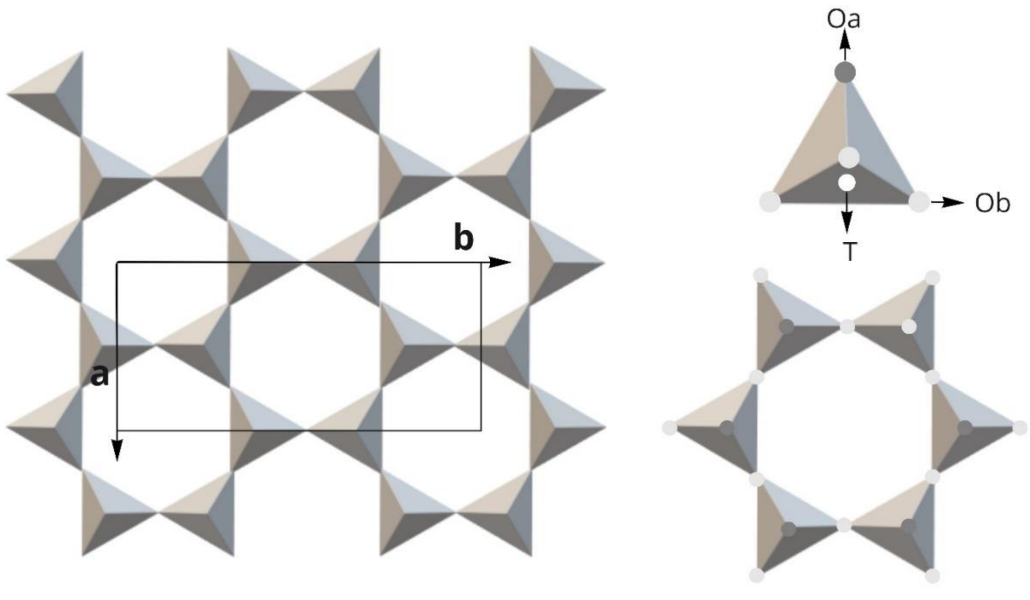

Figure 2-8 A tetrahedral sheet consisting of tetrahedrons as illustrated in the right upper corner. Oa and Ob refer to the apical and basal oxygen atoms. T is the cation. The right bottom corner explains how the basal oxygen is sheared between the tetrahedrons—figures based on ref [47].

The second building block is an octahedral sheet consisting of several octahedrons [47], [48]. One octahedron consists of a cation, O coordinated by six oxygen atoms forming a hexagonal close-packed lattice. By sharing edges, the octahedron is linked into an octahedral sheet. A pseudo- hexagonal symmetry is created, and both layers are orientated along the a and b crystallographic directions. The most common octahedral cations are Al3+, Fe3+, Mg2+ and Fe2+. The octahedral sheet, as illustrated to the left in Figure 2-9, is made of two different octahedrons, as illustrated to the right in Figure 2-9.

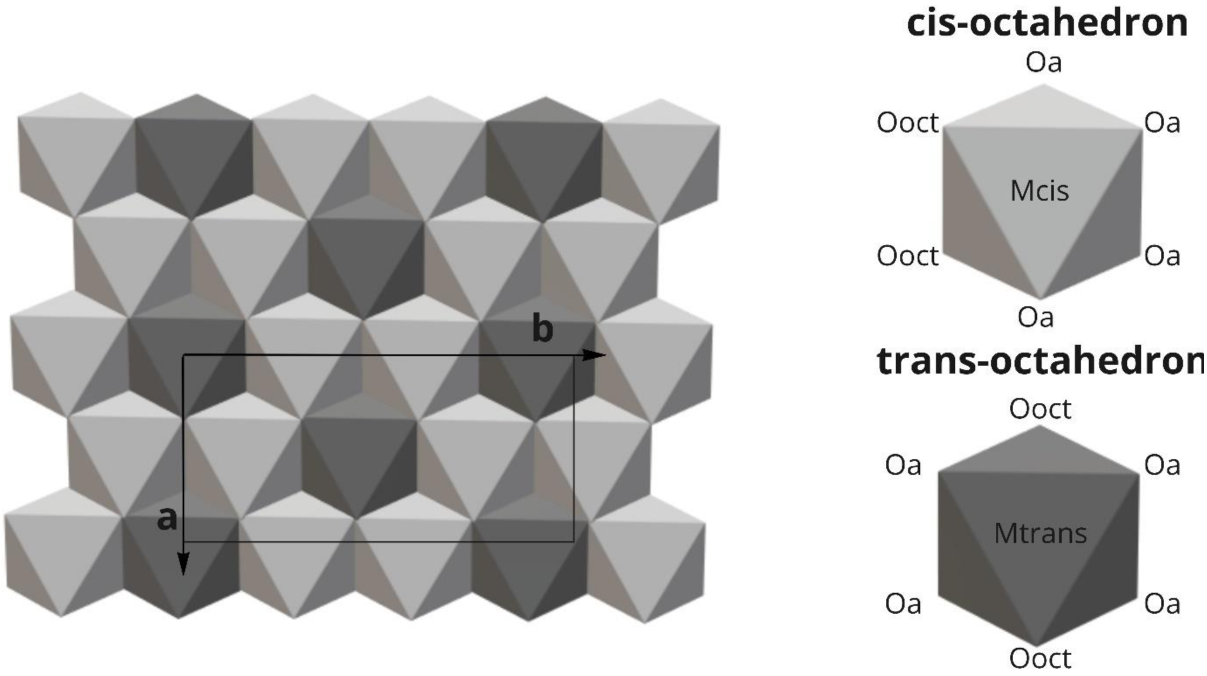

Figure 2-9 The octahedra sheet is illustrated to the left, and the cis- and trans-octahedrons that make up the octahedra sheet are presented to the right. Oxa and Oxb refer to the apical and basal oxygen atoms. Figure inspired by ref [47].

These two building blocks are combined in two main groups, often called 1:1 and 2:1 clay minerals, as illustrated in Figure 2-10 [48], [49]. The free corners of all tetrahedra point to the same side of the sheet and connect tetrahedral and octahedral sheets by sharing oxygen atoms, building a 3-dimensional structure. The non-shared corners in the octahedra are occupied with anions. The different layers are bonded together with van der Waal's forces. The layers can have no charge or a net negative charge depending on the composition of the tetrahedral and octahedral sheets [47].

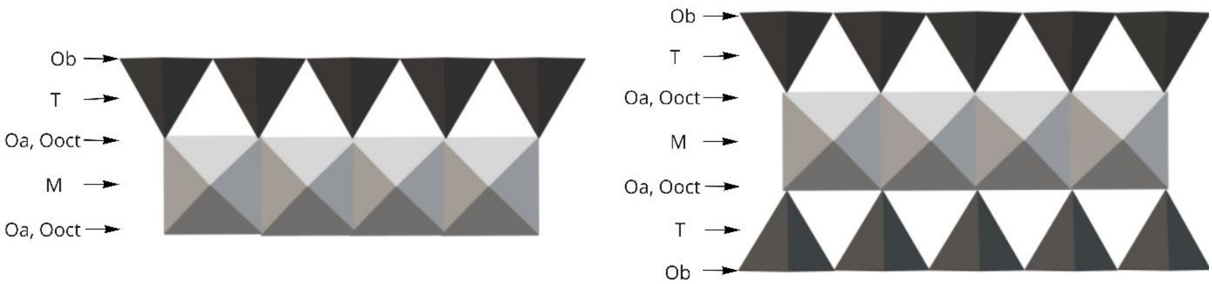

Figure 2-10 1:1 clay mineral to the right and a 1:2 clay mineral to the left. Figures based on ref [1].

In the 1:1 layer, one tetrahedral sheet is connected to one octahedral sheet. One unit cell consists of four tetrahedral sheets and six octahedral sheets in each layer [47], [48]. Kaolinite is the most common 1:1 layer structured clay mineral [1].

In the 2:1 layer, two tetrahedral sheets are connected to one octahedral sheet. One unit cell consists of eight tetrahedral sheets and six octahedral sheets in each layer [47], [48]. Illite and Montmorillonite are 2:1 layer clay mineral.

Studies where kaolinite, illite and montmorillonite were compared all authors agreed that kaolinite was the most reactive clay mineral [1], [50] . However, clay mainly composed of Illite and smectite could also be a suitable raw material for preparing blended cement. This makes it easier to use clay as a SCM since clay distributed worldwide consist of a combination of the clay minerals [1]. Furthermore, different types of clay with varying content of kaolinite, illite and montmorillonite give the clay different properties in terms of strength, pore characteristics and shrinkage, both for the natural and calcined clay.

2.3.3 Calcinated clay

When using clay as a substitution for parts of the cement, it is essential to ensure that the clay has good enough binding properties [46], [1]. For a concrete structure, early age strength is demanded and necessary. The clay minerals are activated by calcination, which alternates the original structure. The calcination process increases the pozzolanic activity in the clay.

Clay is calcinated by a heating process, and the optimal calcination temperature where the clay becomes most reactive varies depending on the clay mineral [1]. The optimal temperature counts between 700-800 degrees Celsius. In addition, the temperature should not exceed 900 degrees calcium since this can lead to recrystallisation of high-temperature phases and decreasing reactivity of the material. After the calcination, the clay must be pulverized again before being used as SCM.

The thermally treated clay react with water, and the calcined clay can be used as a pozzolanic material to consume CH, forming additional hydration products C-A-S-H [51]. The degree of thermochemical activation depends on the mineralogical composition, structure and lattice defect. The result is a more refined microstructure with smaller pores and reduced permeability, which improve the durability of the concrete.

Thermally activated clay with a high amount of kaolinite is prefered as a SCM [52]. The dehydroxylation during the calcination process frees up the aluminates in the structure leading to the formation of metakaolin. However, suitable reactive material can be produced when thermally activating less pure kaolinite clay [51]. An indicator of the quality of the calcined clay is the number of reactive silica. The minimum content should be 25 wt. % according to the European cement standard EN 197-1. [51]

2.3.4 Clay as SCM

The use of pozzolans in construction is an old procedure and can be dated back to the days of ancient Rome [1]. Adding SCMs have shown to have other benefits beyond reducing the CO2 emission. Correct use of SCMs will improve the interfacial transition zones between the aggregates and cement paste and minimize pore size, permeability and calcium hydroxide content of the hydrated products [37], [34]. This results in improved durability mainly in terms of improving impermeability, resistance to thermal cracking, and alkali-aggregates expansion [34].

The most important factor is that the material that cement is substituted with contains CaO, SiO_2 and Al_2O_3. Many natural and industrial byproducts have pozzolanic properties [2, Ch. 6]. There is little information about different SCMs used in Nepal. India, most likely, is the country that will be the most representative. An overview of different types of SCMs used in India are described in Figure 2-11 [53].

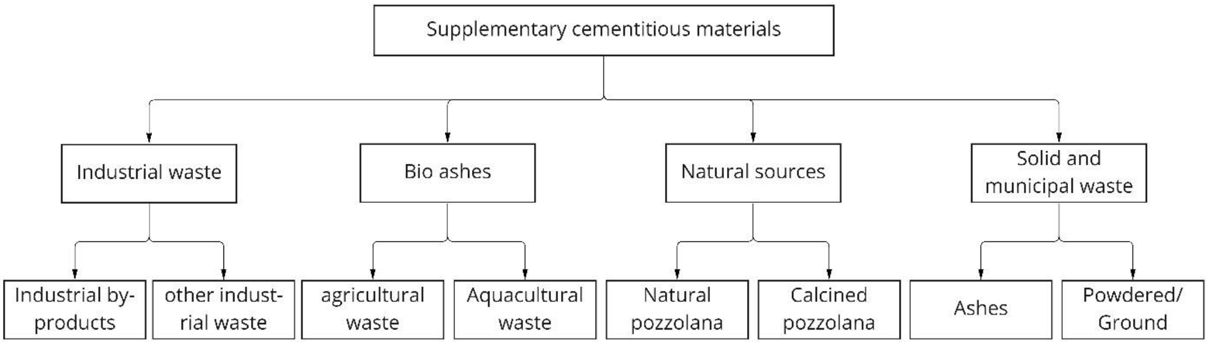

Figure 2-11 SCMs categories. Based on and adapted from an Indian report about the available SCMs in the area [53].

Clay is a natural sourced SCM. The amount of silicate, alumina and iron decide the pozzolanic activity in the clay. In unheated clay there are several physical and chemical properties that inhibit their pozzolanic activity [50]. Clay minerals have stable structures leading to low chemical solubility and low release of alumina and silicate ions. However, most clay minerals behave pozzolanic to some extent. An investigation showed some of the clay minerals behaved pozzolanic in the order [50]:

$$kaolinite > montmorillonite \sim mica \sim Illite > pyrophyllite$$

An investigation where unburned clay was combined with lime, a pozzolanic reaction forming small amounts of new hydration products could be observed after about a month [1]. However, the monitored reactions were too slow and did not give any positive contribution to early age strength which was necessary and required. Therefore, utilization of unheated clay is excluded in blended cementitious formulations. When added the strength properties seem to decrease. Experimental tests where 5 % by volume of the cement was replaced with uncalcined clay the later strength was reduced, but not necessary the durability, which it is concluded that need to be further investigated [54]. It was assumed that this was the result of alteration of the porosity.

Calcination of the clay is therefore often preferred to increase the pozzolanic activity. As described in chapter 2.3.3 the thermal treatment destroys the crystal structure of clay minerals, and the structure become amorphous and very reactive [50]. When the cement is blended with the calcinated clay, the following reaction between the metakaolin and lime occurs [1]:

$$C5\,H + 2AS_2 + 5H \rightarrow CSH\ or\ CASH\ phases$$

The result is reduced porosity and a higher amount of binding phases, furthermore, increased durability and in some cases increased strength. The factors having effect on the physical properties of the clay used as pozzolan are [50]:

- Total content of silica, alumina and iron oxide
- Burning temperature
- Duration of burning

Calcinated clay is also used in combination with lime, and the combination allows for high level of clinker substitution [32]. The definition LC3 is often used about the blend clinker, clay and limestone. The weight ratio 2:1 between clay and limestone is preferred [51], [52], [55]. Replacement level up to 50 % is possible when using LC3. In some cases using LC3 can even result in improved long term compressive strength compared to OPC [56]. This means that the cement content in the concrete can be reduced, at the same time as the OPC strength level is reached and the durabiliy is proven to be good [51]. However, it is not recommended to substitute more than 30 % of the cement in reinforced concrete structures in exposure condition where carbonation induced steel corrosion can be an issue [55].

Similar as for other pozzolanic materials the workability decreases, mainly due to the increased waterdemand affecting the mixing properties when clay is added. Even though the water demand decreases to some extent when the clay is calcinated [50]. Therefore, use of a superplasticizer is necessary to obtain the same w/cm as in mixes with OPC [1].

2.3.5 Environmental impact

The production of cement has a significant effect on the environment [8, p. 44], and the component accounts for 88 % of the CO2 footprint of concrete [57]. The distribution of the CO2 emission from the different components in concrete is shown in Figure 2-12.

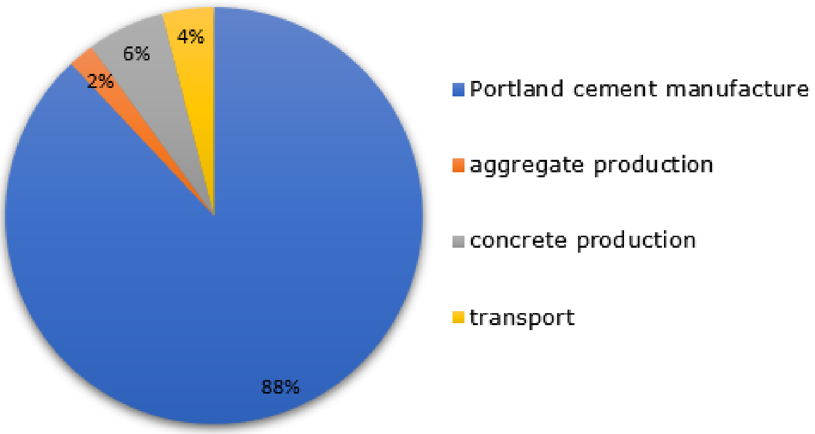

Figure 2-12 CO2 emission concrete, adapted from [57].

The high CO2 emission is due to the physical and chemical processes when covering limestone-based raw materials into Portland cement clinker [51]. The production of one ton traditional Portland cement realizes approximately one ton CO2 [36]. The manufacturing of cement accounts for 8 % of the total CO2 emissions, and the yearly emission is 2.8 Gtons. This makes it the largest current single industrial emitter of CO2 [58, p. 1], [36]. In addition, it accounts for 2-3 % of energy use. Projections foresee 50% increase in annual production of cement to be expected by 2050 [36], meaning that the greenhouse gas emission also will increase in the future. From an environmental perceptive, as the figure indicates, reducing the amount of cement is the most efficient measure.

The cement industry has faced significant pressure and made an effort to improve its production efficiency when it comes to environmental impact [59]. However, the improvements are insufficient to meet the increased demand while achieving low CO2 emissions. Lessening the amount of clincker needed is the most efficient measure to reduce

CO_2 emission since it covers both the CO_2 from the raw material and the fuel combustion [51]. Using SCMs make it possible to prepare more environmental friendly concrete by replacing cement partly or entirely [2, Ch. 1], [51], [53], [37]. The global geological availability of clay is high, but at the moment, only a few countries use calcined clay in cement [51]. An assessment was done in Cuba where the economic and environmental impact of three different cement materials were assessed and compared [59]:

- Stardand OPC. (In Cuba, it is made with 5% of calcium carbonate)
- PPC produced with 15% Zeolitic tuff (natural pozzolan)
- Limestone calcined clay LC3, consisting of 50 % clinker, 30% calcinated clay and 15 % limestone (unburned)

The assessment considered LCA from cradle to gate. The result shows that LC3 was the most energy and cost-efficient alternative. Berriel et al. conclude that LC3 has a [59]:

> *"great potential to provide a viable opportunity to meet and increase in cement demand with low CO_2 released".*

The study was based on cement production and use in Cuba. Still, the results from the study can be transferred to other countries if the transport distance from the clay deposits to the cement plant is limited to 100 km by truck and the availability of a reliable source of alternative fuel cannot be provided for the production of clinker. Another advantage is that it is not a byproduct and therefore not requiring production facilities. The use of calcined clay in cement is expected to grow in regions with no access to alternative SCMs.

2.4 Earthen materials

2.4.1 General information

Earthen materials have been used for centuries, and throughout time the materials have gone through adaptions and modifications [60]. In addition, new innovative construction methods using earth have been introduced. All earth based materials consist mainly of soil, and in modern times adding cement has become more and more common [26]. Earthen materials that are not stabilized have little strength and should only be used for smaller structures. In modern construction industry stabilizers are therefore frequently used.

2.4.2 Soil

Soil is a complex material, and the properties and composition of the soil is crucial for the quality of the final product. Some factors influencing the properties are [27], [28]:

- The area it is extracted from as clay changes according to climate and nature of the bedrock.
- The vegetation and areas with a large amount of vegetable debris have a negative influence and should in general be rejected for use in construction.
- The dept the material is extracted from influence the quality of the soil. Organic matter is mostly found in the topsoil and should be avoided since it can lead to high shrinkage, biodeterioration and increase the probability of insect attacks.
- Organization of particles during sedimentary process.

Soil consists of particles of varying size, and is often divided into clay, silt, sand, and gravel. Table 2-7 shows an overview of the different components, the grading limits for the size distribution and property description.

Table 2-7 Grading limits from a book about earth constructions that are used in Nepal [26, p. 165]. Geotechnical definition in Parenthesis [39, p. 119]

Component	Description
Gravel	Consists of pieces of rocks with varying hardness. Stable; does not have any changes in properties when in contact with water. Does not have any cohesion when dry. Size range: approximately 5- 100mm.
Sand	Consists of grains of minerals. Lack cohesion when dry but has a high degree of internal frictional force. When slightly moist some cohesion emerge. Size range: 0.08-5 mm (0,06-2 mm)
Silt	Consists of pieces of rocks with varying hardness and size in the range between approximately 5- 100mm. Size range: 0.002-0.08 mm (0,002-0,06 mm)
Clay	Consists of mainly microscopic specks of minerals. Cohesion characteristics are found in clay. It is unstable and will react when in contact with water. Size range: smaller than 0.002 mm (< 0,002 mm)

Since gravel, sand and silt do not have any cohesion when dry, they cannot be used on their own as building material [26]. Clay acts like a binder keeping the coarser particles together, by displaying colloidal interactions and adhesion forces between fine sand and grains [61]. Studies point out that clay minerals that are more or less non-expansive, such as kaolinite and illite are preferable in earth construction, whereas kaolinite is non-expansive due to the 1:1 layered structure.

Soil can, depending on the water content, be in a liquid, plastic, or solid state. The plasticity limited is the water content needed for the soil to go from plastic state to liquid state. This value indicates the ability of the soil to undergo irreversible deformation while still resisting an increase in loading. A common procedure for measuring plastic limited state is described in BS- 1377-2, 1990 [27]: The soil is sieved, and the soil particles sized 0.00475 mm or smaller are dried. Then the soil is added water and rolled out by hand on a flat surface. When the watered soil no longer can be rolled to a 3 mm diameter thread without breaking the plastic limit state is reached.

Optimum moisture content varies to some extent depending on the soil, and should normally be determined by experimental tests before soil from a new area is used . the values are usually between 11- 15 % [27]. The moisture content of the clay on site must be determined. Then the soil is either watered or dried until OPC is achieved. When cement is used to stabilize an earthen material it is recommended that the amount of added water should be increased by 2 % in order to account for evaporations during processing [27].

Approximation of the optimal moisture content can easily be achieved using the drop test. A ball of moist soil with d=40mm is compacted by hand and dropped onto a hard surface from a height of 1,5 m. If the soil has an OMC, the ball will only break into a few pieces.

2.4.3 Composition

Rammed earth and CSEB are composite materials consisting of clay, aggregates and water [26]. In addition cement is often used as an additive, and the material can be divided into two categories; stabilized and not-stabilized earth materials [62].

Ideal distribution of the particle size is important in order to increase the mechanical strength and weathering resistance [27]. It is advantageous to minimize voids ratio in order to increase the contact between soil particles. Theoretically soil with no voids can be achieved if the soil particles are spherical and the size distribution follows the Fuller formula [27]:

$$p = 100\left(\frac{d}{D}\right)^n$$

Where p is the amount of grain for a given diameter, d is the diameter, D is the largest diameter and n is the grading coefficient. Through years of experience, it has become common to use the distribution given in Table 2-8.

Table 2-8 Distribution of the different components in Rammed earth and CSEB given in volume [26, p. 17], ,[27], [63], [64].

Component	Rammed earth	CSEB
Clay	15-30 %	20 %
Silt	20-35 %	15 %
Sand	40-50 %	50 %
Gravel	0-15 %	15 %

When cement is used to stabilize the material, it is usually added by a weight percent of the mix. In rammed earth structures proportions between 4 wt. % and 15 wt. % are used, usually 6- 10 wt. % [26], [27]. In CSEB between 5-10 % is added [63], [64].

2.4.4 Properties eathen materials

The properties vary significantly, and it is difficult to give exact values [27], [63], [65]. All types of earth constructions have relative good strength in compression, but poor strength in shear and tension. First and foremost, the properties of the material depend on several factors such as compaction, strength of the components, and MC. An indication of the different values is given in Table 2-9. The reinforcement is usually casted into the foundations and run up to the wall. The walls are then better prepared to withstand the horizontal forces associated with earthquake. In addition, the reinforcement will contribute to strengthen the walls and increase the resistance against tensile forces.

Table 2-9 Approximately values for some important properties [27], [63], [65]. The values will depend on several factors, and may deviate from the given values.

Properties	Rammed earth	CSEB
Dry density	1700-2200 kg/m^3	1700-2200 kg/m^3
Young’s Modulus, E	500 MPa	700-1000 MPa
Compressive strength	0,5-6,5 MPa	3-6 MPa
Tensile/Bending strength	10 % of comp.strength	0,5-2 MPa
Shear strength	0-7 % of comp. strength	0,4-0,6 MPa

Earth based materials containing clay will swell when in contact with water, and shrink when dried [27]. This may result in failures, so it is important to control this phenomenon. Swelling and shrinkage in the material are depending on the clay present, soil grading, and moisture content, and can only be predicted by experimental data. Concerning the soil in Nepal, it is common that the value for shrinkage due to air drying is between 02-2 mm/m, and the water absorption is between 5-20 %.

2.4.5 Rammed earth

Natural soil is available in a large range of colors. Red colored soil is often preferred in rammed earth constructions [26], [27]. By using additives such as lime and cement or by mixing different kinds of soil, different properties and colors can be varied. Rammed earth has proven sufficiency to construct buildings with as much as 10 stories, even without the use of design standards [27]. However, the majority of rammed earth buildings are low rise, single or two story buildings, and the stresses experienced by the thick earth wall are generally well within the capabilities of the material.

Rammed earth is an ancient building method and is a type of unbaked earthen construction [62], [66]. The construction technique is primarily used to build walls, but it can also be used for floors, roofs, and foundations. In the Nepali earthquake design standard, some few requirements are given that should be followed to secure sufficient quality and capacity. The given requirements are presented in Figure 2-13. In addition to use the dimensions as showed in the figure for larger scale projects, reinforcement is added to improve the strength.

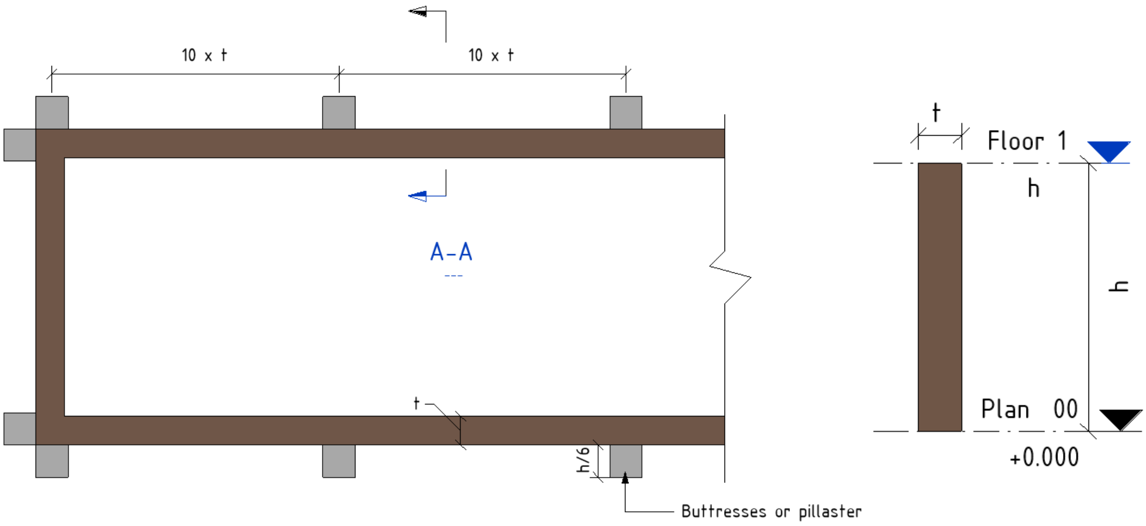

Figure 2-13 Pilaster or buttresses should be provided when the span extend 10 times the thickness of the wall. The height of the wall should be between 1,8 m and 2,5m m. The thickness of the wall should be minimum 400-450 mm. Figure based on ref [33].

The construction method for rammed earth walls has several similarities to construction of concrete walls. Most commonly the building technique is used to build the elements in-situ [27]. However, in the latest years prefabricated rammed earth walls have been used in a very small number of cases. This may be more common in the future, and potentially increase the quality and lessen uncertainties associated with construction on site.

The walls are made by tamping loose moist soil in in a rigid temporary framework [62]. The framework is typical made up of straight wooden planks with as few knots as possible. When building the framework, it is important to obtain a smoot surface on the inside and to prevent lumps of earth from sticking to the framework giving the walls an uneven surface. All vegetable matter must be removed from the soil before it can be used: grass, buts, stray or hay, splinters of wood. Then the earth needs to be dried to afford adequate cohesion [26].

Then construction of the wall can start, as illustrated in Figure 5-1 which illustrates the construction process [67]. During construction it is important that the earth is preserved and sheltered for rain since it is impossible to tamp earth that has been soaked by water.

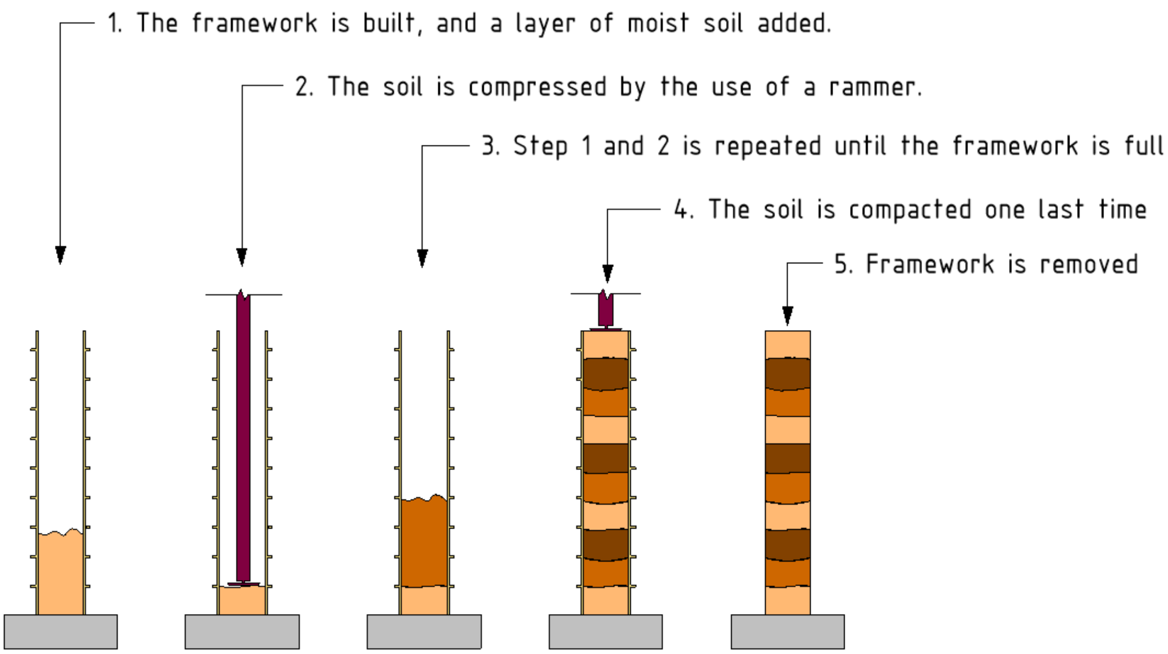

Figure 2-14 Construction of rammed earth wall. Figure based on ref [67]

The soil is typically added in layers of 100-150 mm, maximum allowed layer height given in NBC204 is 450 mm [33]. The clay is then compacted traditionally by using manual rammers. Nowadays, pneumatically powered dynamic rammers are more common to use for this process worldwide. In the NBC204 a mallet (a timer hammer) is specified as the preferred type of rammer. It is also recommended that the next layer is not started on until the next day, and preferable first after two days. The framework is removed almost immediately after the last layer is added, giving the wall the opportunity to dry.

2.4.6 Compressed stabilized earth blocks

Compressed earth blocks were first introduced in the 19th century [68]. Then rammed earth was compressed into small frameworks formed as bricks and manual rammers were used to compact the moist soil. Today it is common to add stabilizer to the soil resulting in the term CSEB often being used. CSEB is a heterogeneous and anisotropic composite construction material, and the blocks are held together by mortar [65]. The properties of the finished structure can vary significantly considering that both the blocks and the mortar can have several composition and shapes.

The bricks are made by mixing soil, cement and water [63]. Then the mixture is compacted into bricks by using a manual or mechanical steel press. One type of steel press is illustrated in Figure 2-15. After being compressed they are stored for 21 days, and the blocks are hydrated to gain strength. The cement sets and bond with the sand stabilizing the blocks, and the compression in the machine add density and strength.

The shape of the blocks varies and often depends on the project in which it shall be utilized, and often can bricks with different shapes be made in the same machine, as illustrated in Figure 2-15 [69], [63]. It is often hollows in the blocks, reducing the weight, and thereby reducing the amount raw materials needed to produce the CSEB. For a block to obtain the wanted quality, all angels should be straight, and the form of the block should be rectangular and uniformed.

Figure 2-15 Illustration of a machine used to make CSEB, and three different blocks that can be made using the same machine [69].

The mortar is either a mix of sand, cement and water or a mix of sand, clay and water, first most common today [65]. Considering both the block and the mortar being strong in compression and weak in tension, the material is only suitable for components mainly loaded in compression. In addition, the joints between the materials are weak in tension and fragile when subjected to shear stresses.

Compressed Stabilized Earth Block (CSEB) technology makes it possible to use local soil, and the bricks are made by compressing moist earth in a steel press [68]. Both manual and mechanical presses are used. The only component that needs to be transported is cement, and in some cases reinforcement. Considering that only small amount of non-local materials is used in CSEB structures the method is suitable for rural areas [70].

2.4.7 Environmental impact

The increased focus and demand for more sustainable buildings due to the environmental challenges have led to a growing interest among professional builders to increase their knowledge about building with earth materials [62], [61]. In general, earthen materials have smaller CO2 footprint compared to modern materials. Studies have been conducted on the environmental impact of using earth based materials, two of them for structures in Nepal are suberized below. Several references underline the conclusion given in the case studies, among them [63], [64], [71].

The case study by Pandey et al. [60] calculated the total embodied energy of using rammed earth for a school building in Mustang, Nepal, and compared it by utilizing both burned clay bricks and concrete. While burnt bricks and concrete have an embodied energy of 3-4 GJ/m2 and 4-10 GJ/m2 respectivly, the result of using just rammed earth showed an emodided energy of 1,15 GJ/m2.

A company called *Build up Nepal* compared the environmental impact of using CSEB and fired bricks for housing. LCA analyzes were made for using these materials for a 3,5 room house, and them compared. The result showed that using CSEB ended in a total CO2 emission per house of 7,16 kg CO2, while using fired bricks resulted in a CO2 emission of 10,69-12,79 kg CO2, depending on the use of stone mortar or brick mortar in the foundation.

3 Methodology

3.1 Research strategy

The thesis covers a broad theme and two different alternatives for making the building practice in Nepal more sustainable, were evaluated. In order to achieve the objectives of the project, different research strategies were applied, as illustrated in Figure 3-1.

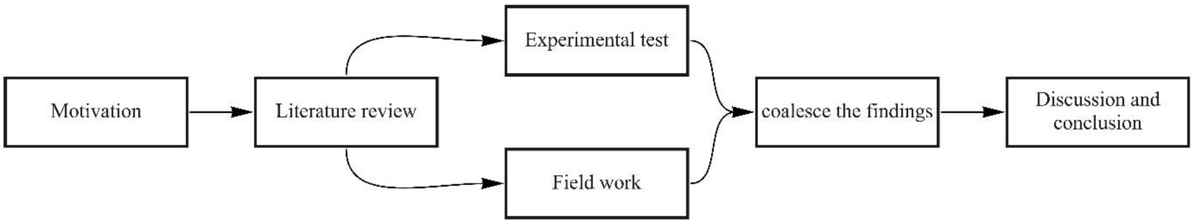

Figure 3-1 Flow diagram of the working process and methodology utilized in the project.

3.2 Literature review

3.2.1 Purpose and overview

A literature review is said to be the foundation for all types of research, and it is essential to justify future research [72], [73]. A review of literature relevant to this project has been carried out to find and map relevant information. A semi-systematic approach for this review was developed, which Snyder describes in ref [72].

The research questions cover two different alternatives for achieving the same goal, resulting in a broad spectrum of relevant information. Therefore, using a literature review was essential to get an overview of the subjects. The results are presented in chapter 2.

3.2.2 Conducting the review

The study was a circular process, and how it was conducted is illustrated in Figure 3-2. By structured searches, an adequate amount of relevant literature has been found.

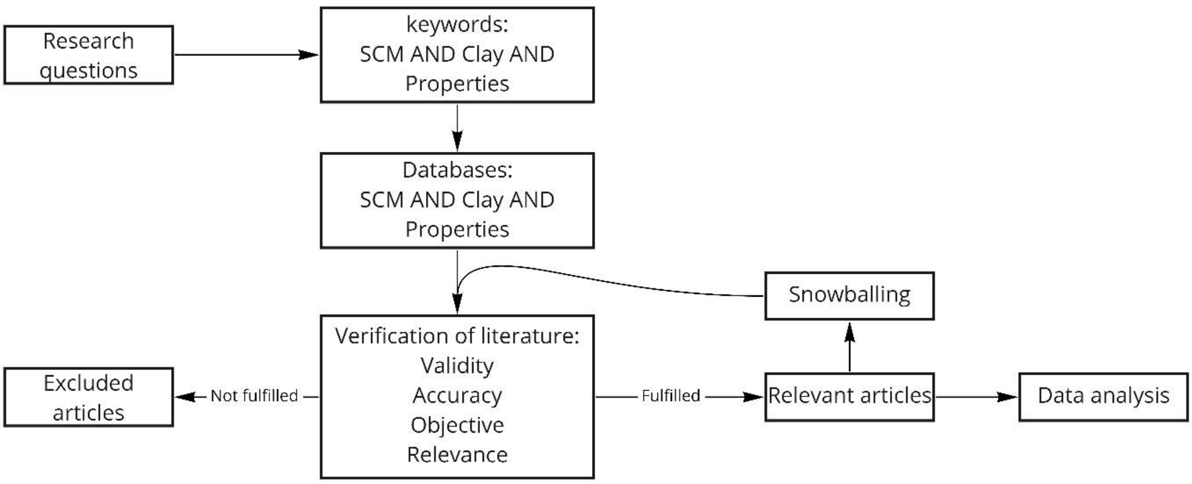

Figure 3-2 Overview of how the literature review was conducted. It is inspired by Figure 2 in the report by Thonemann et al., and adapted for this project [74].

Different keywords and phrases were used to find academic books, compendiums, research articles, review articles, case studies and relevant websites. First, some words and combinations were tested. Then, synonyms and alterations of these keywords widened or narrowed the searches. Some of the searches were also done in Norwegian. In those cases, the Norwegian translation of the words was used. Typical searches often consist of two to three keywords, and the most frequent used searching words are presented in Table 3-1.

Table 3-1 Overview of some of the most frequently used keywords

Research question 1		Research question 2	
Cement	SCMs	EPD	CSEB
Components	Pozzolan	Sustainable	Earth-based
Hydration	Pozzolanic	Environmental impact	Materials
Clay	Clay minerals	LCA	Concrete
Lime	Mineralogy	CO2	Mixing
LC3	Kaolinite	Emission/ footprint	Composition
Chemical composition	Illite	Costs / Low cost/	Burned bricks
Unheated	Binder	Affordable	Low cost
Untreated	Properties	Availability	Affordable
Not calcinated	Composition	Production	Properties
Calcination	Process	Preferences	Strength
Calcinated	Production	Rammed earth	Workability
Heated	Availability	Building codes	Durability
Nepal	Limitation	Requirements	Nepal

In addition to conducting searches, as illustrated in Figure 3-2, some searches were done directly on different websites that are known for reliable information:

- UN's official website for information about Nepal.
- Website for the Nepali standards was used to find information about the building standards and rules that applies to the country.
- Byggforsk.no for information about concrete and cement.

The literature found by searches following the steps in Figure 3-2 or direct searches in one of the websites was then sorted and saved according to categories. After an adequate amount of literature was found, the information was analyzed and placed in context before it was implemented and adapted for this project. Also, this was a circular process, and during the analysis, it became clear that additional information about some subjects was necessary to obtained. Then, new searches following the steps in Figures 3-2 were conducted.

3.2.3 Evaluation of the literature review

The review has made it possible to get an overview of a large range of information, and an overview of the existing literature regarding the subjects has been mapped. Considering the searches were so broad, it is not easy to cover all relevant articles. However, the found information has made it possible to get an overview of the situation of the day and gain insight regarding the alternative solutions.

Little information is to be found regarding the use of clay as a SCM in Nepal, mainly because it is not very common. Therefore, information about using clay as a SCM in other countries has been used. It is also little information about the inhabitants' preferences and the social effects by using concrete or other materials. Some studies have been conducted to map what the locals think about using RCC. However, the assessment is relatively limited, and the information may not be representative. The studies can, though, indicate the situation and what people think about RC structures and are therefore referred to in the report.

3.3 Experimental tests

3.3.1 Purpose and assumptions

The tests were conducted in the lab at NTNU in Trondheim, and the purpose of the lab was to indicate whether unheated clay can be used to replace parts of the cement. The results are shown in Chapter 4. It was examined how the compressive and bending strength changed when 10 %, 15 % and 50 % of the cement were replaced with unheated clay. Additionally, the workability was evaluated by using a slump test on the fresh concrete.

Initially, clay from an area in Nepal was supposed to be tested to see how clay from the relevant area influenced the properties of the concrete. However, several factors made this impossible. Therefore, it was decided that clay from Trondheim should be used instead. Clay properties can vary significantly. Therefore, using clay from Norway can be justified since the quality, clay mineralogy and chemical composition can vary just as much within different areas in Nepal.

It is not easy to make an accurate replica. It is impossible to sieve out just the clay fraction when using clay directly from the soil in the concrete mix with available on-site equipment. The actual fraction amount with binder properties is difficult to predict. Therefore, it was decided not to sieve out the clay fraction since this is not likely to be done in practice in Nepal.

Predicting the amount of water needed to obtain a concrete mix possible to work with was difficult considering that clay drastically increases water demand. A pre-determined water/binder ratio of 0,5 was used as a starting point when mixing the components. Then additional water was added during mixing, and the w/cm was calculated. This is not optimal when the results are compared. However, the procedure is similar to how it is done in practice at the construction sites in Nepal, where water is added until the concrete is workable. Therefore, this alternative seemed most adequate.

3.3.2 Material recipe

The particle-matrix model and a proportioning calculator from NTNU are used to calculate the different amounts of the components. The recipe is based on principles used in Nepal. The volume ratio between coarse and fine aggregates is 1:2. The volume ratio between cement and aggregates varies depending on the wanted strength. In this project, a matrix volume of 300 and particle volume of 700 are used as a starting point for mixing. Then it was calculated for air content equal 2 %, and since the mix containing clay was added additional water the mixes ended up with different matrix and particle phase volume. The ratio between the dry component where kept constant.

An overview of the matrix phase is presented in Table 3-2. Some important properties of the binding elements are:

- The cement has a density of 3080 kg/m3.
- The clay is from Dødensdal in Trondheim and has a density of 2850 kg/m3. The clay fraction varied between 44-77 %.

Table 3-2 The matrix phase consists of cement, clay water, and fine aggregates smaller than 0,125 mm.

Components	Refrence	SCM10	SCM15	SCM50
w/cm	0,5	0,6	0,9	1,1
Cement	356,8 kg/m^3	307,4 kg/m^3	261,9 kg/m^3	143.4 kg/m^3
Clay	-	34,2 kg/m^3	46,2 kg/m^3	143,4 kg/m^3
Water	178,4 kg/m^3	209,5 kg/m^3	23,53 kg/m^3	322,65 kg/m^3
Fine aggr*	7,9 kg/m^3	7,6 kg/m^3	6,85 kg/m^3	6,45 kg/m^3

The particle phase is constant in all the mixes. "*Årdal 0/8 mm naturlig vasket"* and "*Årdal 0/8 mm"* were mixed to obtain a mixing ratio of 1:2 between fine and coarse aggregates, see Table 3-3. Fine aggregates are defined as al particles smaller than 0,475 mm and coarse aggregates are all particles larger than 0,475.

Table 3-3 The particle phase consists of fine and coarse aggregates.

Components	Refrence	SCM10	SCM15	SCM50
Fine aggr.	610 kg/m^3	575,6 kg/m^3	519,9 kg/m^3	489,5 kg/m^3
Coarce aggr.	1229,4 kg/m^3	1182,7 kg/m^3	1068,4 kg/m^3	1005,9 kg/m^3

3.3.3 Tools

The tools used in the lab work are presented in Table 3-4 with a description. How the tools are used is closer described under the method description for each area of usage.

Table 3-4 Tools used in the lab work

Are of usage	Equipment	Description
Preparation of clay	Plastic paper	Thick plastic that withstands hammering.
	Hammer	Heavy mental head with timber handle.
	Steel tube	Circular tube to roll back and forward over clay.
Mixing	Hob + boiler	Regular hob and a steel boiler for heating.
	Weight scale	Shows weight in grams with to decimal accuracy.
	Mixer 11l.	Manual mixer that can mix 11 l concrete.
Slump test	Slump cone	Formed as a truncated cone with a base diameter of 20 cm and top diameter 10 cm. Height 30 cm
	Tamping rods	Steel rods.
	Ruler	Regular ruler 30 cm to measure the slump.
Casting	Formwork	Rectangular (40 x 40 x 160 mm) and cube (100 x 100 x 100 mm) formwork in steel.
	Spray	Used in the forms to prevent the concrete from sticking to the formwork.
	Hammer	A plastic hammer.
	Tamping rods	Steel rods.
Testing	compressive strength tester	Tony Technik compressive strength tester for 100 x 100mm cubes.
	Bending and compressive strength tester	Tony Technik combined compressive and bending strength tester. Normally used for testing of cement and mortar.

3.3.4 Preparation of clay

The clay was previously used at another lab at NTNU and arrived in the shape as presented to the left in Figure 3-3. The clay was then placed between plastic sheets and crushed with a hammer. After that, a steel tube was used to roll over the clay to pulverize it.

Figure 3-3 Clay before and after the pulverization

3.3.5 Mixing procedure

First, all the dry components were weighed and added to the mixer in the order of cement, clay, sand, and aggregates. The mixing process is described in Figure 3-4 and is based on the standard procedure at NTNU, with some minor adaptions to fit this project. This is similar to the mixing approach at construction sites in Nepal, where an amount of water that is supposed to be added is given in the recipe. However, if the mix is not workable additional water is added. Therefore, it is assumed that if this mix had been used at an actual construction site, extra water would have been added until the workers could easily cast the concrete mix.

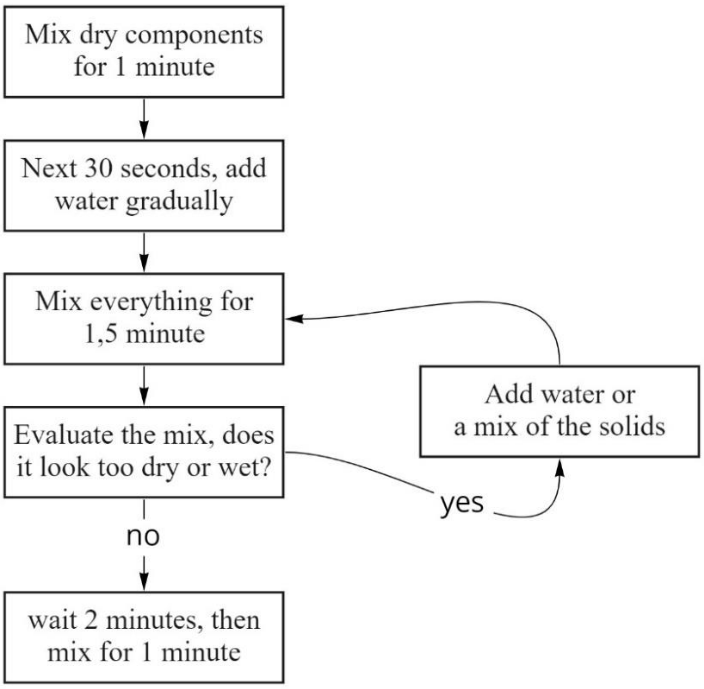

Figure 3-4 Mixing procedure. Initially, a w/cm equal to 0,5 was used; as expected, it became clear that more water was necessary for the mixes containing clay.

Some pictures from the mixing process and one example of a mix where it was necessary to add additional water are illustrated in Figure 3-5.

The needed amount of the various components were weighed to achieve approximately seven litre concrete based on the recipe.

Figure 3-5 The different components were weighed and then mixed. Picture illustrating the mixing process, a mix where it was necessary to add extra water is shown.

3.3.6 Testing of fresh concrete

The slump test is one of the most common methods to control how easy the concrete is to cast [75].

- The slump cone was filled with concrete in three rounds
- After each round, the tamping rods were used to comprise the concrete.
- Then, over 3-4 seconds, the slump cone was removed.
- The slump was measured from the top of the slumped concrete to the cone.

According to NS-EN 12350-2, the method can be used when the slump is between 10-210 mm. However, the method is used for slump until 240 mm in practice.

3.3.7 Casting of concrete

The concrete was casted in formwork, as illustrated in Figure 3-6, approximately 1/3 of the mix was added and tamped with the tamping rods to remove air and ensure sufficient compaction. Also, a hammer was used to vibrate the concrete to remove air bubbles. This process was repeated until the formwork was full. The formworks had the sizes:

- 100 x 100 x 100 mm cubes
- 40 x 40 x 160 mm prisms

Figure 3-6 Casting of concrete in formwork.

After 24 hours, the formworks were removed. Then, the cubes and rectangular-shaped concrete were placed in a water bath, where they were stored until they were tested.

3.3.8 Testing of hardened concrete

The compressive and tensile strength were tested after 7, 28 and 62 days using the machines illustrated in Figure 3-7. The device to the left was used to examine the compressive strength following the rules given in NS-EN 123903. Cubes with the dimension 100 mm x 100 m x 100 mm were tested using a standard program at NTNU.

In addition, the 40 mm x 40 mm x 160 mm prisms were tested in the combined test machine for compressive and flexural strength according to ISO 679. First, the flexural strength was tested by using a 3 point flexural test. Then, the prism was divided, and the compressive strength was examined on cubes with the dimension 40 mm x 40 mm x 40 mm.

Figure 3-7 To the left a standard compressive strength test machine. To the right the combined compressive and tensile strength test machine.

3.3.9 Additional tests

One reference mix and one mix containing 10 % clay were made. The mixing and testing procedure follow the same steps, as presented in Chapter 3.3.4-3.3.9.

These evaluations were originally not planned for, but were conducted to increase the data foundation. However, since these tests were not intended, it ended up being only possible to test the concrete after 30 days. Therefore, the tests are not complete, and the results are therefore not used in the report. However, since the compressive strength differed significantly from the other tests, the results are given in appendix 2 and are briefly discussed in chapter 4.4. The tests had a different recipe, as described in appendix 2, and the ratio between sand and cement was 1:1,5 between fine and coarse aggregates. Then the total volume ratio was 1:1,8:2,7. Considering the differences from the original tests, the additional test is not directly transferable. The variety of the factors was:

- Higher amount of sand. Mixing ratio 1:1,5 instead of 1,5:3.
- Before the first tests, the clay was stored in a "drying cabinet". Then, the 1,5 weeks from the first test until the additional mix was made, it was stored at room-temperature.
- A bit more cement than in the first mix was added.

It was predicted that the result would be different considering another type of mix was used. However, the result did not show the expected differences. Therefore, it is decided to mention and discuss the result as it is interesting to see how much the result differed from the minor changes in the material recipe.

3.3.10 Evaluation of the exprimental tests

Subsequently, reviewing the results from the experimental tests, it would have been interesting to test mixes where 10 %, 15 % and 50 % of the cement were replaced with aggregates to see if the clay gave any additional strength at all or if it just as well could have been substituted with aggregates. Then it would have been easier to evaluate the influence of the clay. However, the tests serve their purpose as they give a strong indication of the effect replacing cement with clay, or perhaps any other material with a filler effect, has on the finished concrete.

3.4 Field research

3.4.1 Aim of the field research

Understanding how the construction industry works and getting an impression of what people prefer is essential when introducing alternative materials. Fieldwork makes it possible to gain valuable insight, which cannot be done by just reading literature. Field research is a qualitative method [76]. This project aims to implement the information presented by the locals and observations done in the field based on the theoretical framework of the literature review.

Assumptions were made as a result of the literature review, which resulted in a set of specific research questions for the fieldwork and the following hypothesis:

1. In urban areas, concrete is the most used material for all buildings.
2. Most people prefer concrete structures both in the rural and urban areas.
3. Reinforcement is not always used even in the cases it is demanded.
4. There are many unfinished buildings because of high costs, and people do not have the opportunity to finish the buildings.
5. The introduction of new design codes has provided the country with the necessary knowledge to construct buildings of good quality, resulting in improved structures.
6. Providing housing at an affordable price is challenging, especially in rural areas, since the access to raw materials is limited.
7. Providing necessary raw materials in rural areas are challenging.
8. Substitute parts of the cement with unheated clay are most relevant for concrete buildings in urban areas.

9. Substitute parts of the cement with calcinated clay are most relevant for concrete buildings in urban areas.

3.4.2 Preparations

Before the field work was conducted, several preparations had to be performed, which can be divided into two categories: practical and theoretical.

The first practicality was to plan when and how the field research should be conducted. The planning process included which construction sites to visit, how to get there, and how to solve the language barriers. This was done by mail and online meetings. After the how and when were solved all the practicalities that had to be planned in advance started. This involved booking plane tickets, applying for a visa, organizing accommodation, vaccination, and gathering all necessary travel documents. In addition, the mandatory travel safety courses under the auspices of *Engineers Without Borders* had to be completed before travelling. All practical preparations were done in collaboration and with the help of *Engineers Without Borders* and Martina Keitsh that introduced us to the locals, mostly colleagues, friends, and acquaintances of hers.

Theoretical preparations were conducted, aiming at gathering essential information about the country before travelling. This was the most time consuming process, but important as knowledge about the country, its situation, and how the construction industry is working was necessary to understand in order to get the best value of the field study and the time in Nepal.

3.4.3 Data collection

When it comes to the data collection, direct observations and qualitative interviews were used as the main method.

Direct observation is a method where the researcher watches and records activities that are relevant for the specific project [76]. Direct observation can be collected in several ways and in this case, it included field notes, checklists, photographs, and videos. In closed and private settings without the knowledge or consent of the participants, ethical concerns can be raised [76]. Therefore, all the workers at the construction sites were informed before the visits. Observations done in open public spaces are considered acceptable without the participants' knowledge, and are therefore used in some parts of the project. It is common to categorize observations as unstructured or structured.

The unstructured observations are recoded holistically without the help of a predetermined guide or protocol, and the researcher records the observations as field notes [76]. Since little information about the visits where possible to get hold of in advance unstructured observations were mostly used.

However, the visits at the construction sites were structured to some extent. A plan was made in advance in order to plan for structured observations to ensure that important information was properly recoded. This was the preferred method during the field work since it made it easier to ensure that all information collected from observations was well documented. A set of checklists and rating scales were made and used during the visits.

Qualitative interviews are a method where information is obtained by asking questions directly to the participants, usually categorized as informal, semi- structured, and standardized open-ended. [76], [77]. Since the meetings were not planned in advance, it was difficult to prepare structured interviews. Therefore, informal ones were used, mostly after direct observations. The method can in many ways resemble a traditional conversation. Some questions were made in advance. In addition, many of the questions were spontaneously formulated and asked informally.

3.4.4 Visists

The fieldwork was conducted in the time period April 28th to May 6th. The study was conducted in the Kathmandu Valley area, with a base in Patan. The main key person during the field study that helped arrange the different meetings and visits was Sangeeta Singh. She is a Professor in Urban Planning and Deputy Director at the Centre for Disaster Studies at the Institute of Engineering at Tribhuvan University. The companies contributing to the field work were as follows:

- Consulting firm working with concrete. We visited some sites where concrete structures of varying size were under construction guided by one of the engineers working at the office. In addition, the office of the consulting firm was visited.
- *Build up Nepal* is a social business dedicated to fight poverty in rural areas in Nepal. They sell machines and teaches the entrepreneurs to use the equipment making CSEB. The company collaborates with *Engineers Without Borders* in Sweden.
- *Ramro Mato architects* is a firm working with rammed earth. The main architect R.M. Pandey guided a visit at one of the construction sites, and provided insight in the building technique, previous projects, and how the material is used in Nepal.

3.4.5 Analysis

The data analysis was done in two main steps: information was written down during the stay in Nepal, then reviewed more structured and detailed after returning to Norway. From the observations and interviews a lot of information was collected in form of hand notes and pictures. Every evening information collected that day was written down more structured, and additional thoughts and reflections were added. Back in Norway, this information was reviewed once more. Relevant literature was used to confirm some of the information that was unclear after the interviews.

3.4.6 Strength and weaknesses of the method

The utmost weakness was the duration of the field research that lasted just for eight days. In order to understand the culture, and how the construction industry work, a longer period should have been spent in the field researching, and larger parts of the country should have been visited. Additionally, the construction industry in Kathmandu Valley differs a lot from the rest of the country, and, optimally, it would have been useful to travel outside Kathmandu area , where the biggest challenges associated with construction and lack of materials are.

The biggest challenges were linked to translation. When visiting the construction sites, it was a bit difficult to get an accurate answer, and some misunderstandings occurred. For example, it was very difficult to understand how much water they used in the concrete mix. After translation the amount of water added, corresponded to a w/cm equal around 2, which clearly was not the case. However, in the end most questions were answered, but it made it difficult to get answers from construction workers, and people not speaking English. Therefore, the information the fieldwork is based on, is mostly received from civil engineers, architects, and the other people working in the offices.

4 Results experimental tests

4.1 Tests on fresh concrete

The measured slump for the different mixtures is given in Table 4-1, and pictures of the slump in Figure 4-1.Figure 4-1 Pictures of the slump tests (1) Reference mix, (2) SCM10 mix, (3) SCM15 mix, (4) SCM50

Table 4-1 Slump measures. It is important to notice that the different measures cannot be directly compared since the w/cm ratio differs as prescribed in the table .

Concrete mix	Slump measures	w/cm
Reference mix	17,5 mm	0,5
10 % clay	2,3 mm	0,6
15 % clay	14,0 mm	0,9
50 % clay	8,0 mm	1,1

(1) (2) (3) (4)

Figure 4-1 Pictures of the slump tests (1) Reference mix, (2) SCM10 mix, (3) SCM15 mix, (4) SCM50.

All in all, it seems to be necessary to use a superplasticizer in order to obtain the same w/cm as in mixes with only cement. Some comments of the workability and slump test:

- The reference mix had slump measures as desired. It was easy to work with when casted into the formwork. The workability and slump were as expected, considering it was the reference mix.
- The mix added 10 % clay had too little slump. The workability was not good, and the mix was difficult to cast into the formwork. This could be seen when the formwork was removed since some of the surfaces were not entirely even.
- The mix with 15 % clay was added significantly more water improving the workability. The slump was ok, but considering the high w/cm the slump is not very good. In addition, the mix seemed to be a bit separated, and it was clearly more cement/ clay in some parts of the mix.
- The mix with 50 % clay had almost no slump. Considering the very high w/cm a larger slump was expected. The mix was difficult to work with, and almost impossible to cast into the formwork.

4.2 Compressive strength

4.2.1 Compressive strength 100 mm x 100 mm x 100 mm cubes

The key results from the compressive strength tests after 7, 28 and 62 days are presented in Figure 4-2 and Figure 4-3 . Complete results are given in appendix 1. In all the mixes the strength increased over time, the mix containing 50 % had the highest percentage change while the reference mix had the lowest percentage change.

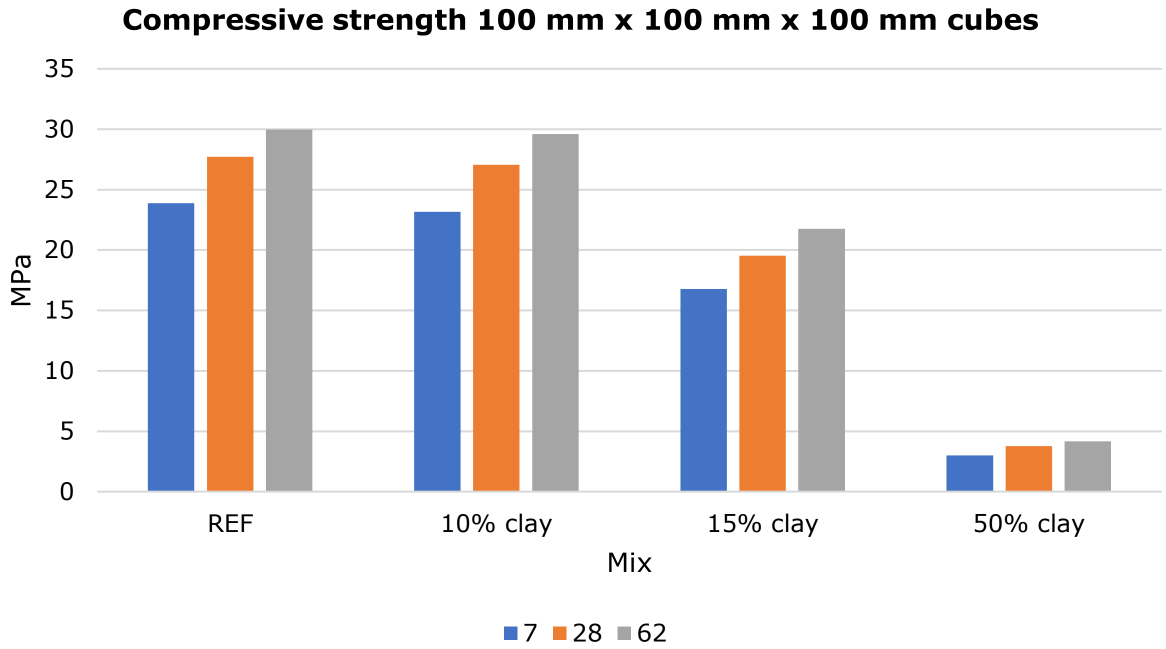

Figure 4-2 Results form 100 mm x 100 mm x 100 mm cube compressive strength tests of the different mixes after 7, 28 and 62 days.

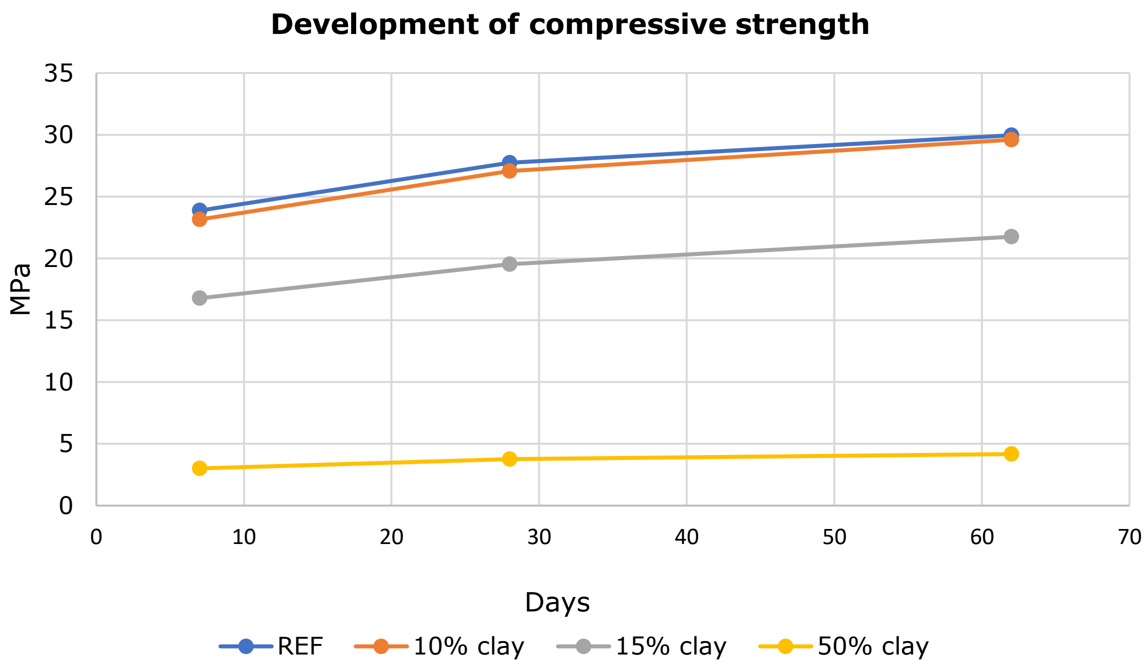

Figure 4-3 Development of compressive strength with time. All mixtures increase in strength, having the highest compressive strength after 62 days.

4.2.2 Results compressive strength 40 mm x 40 mm x 40 mm cubes

The results from the compressive strength after 7, 28 and 62 days are presented in Figure 4-4 and Figure 4-5. Complete results are given in appendix 1. In all the mixes the strength increased over time, the mix containing 50 % had the highest percentage change while the mix with 10 % clay had the lowest percentage change.

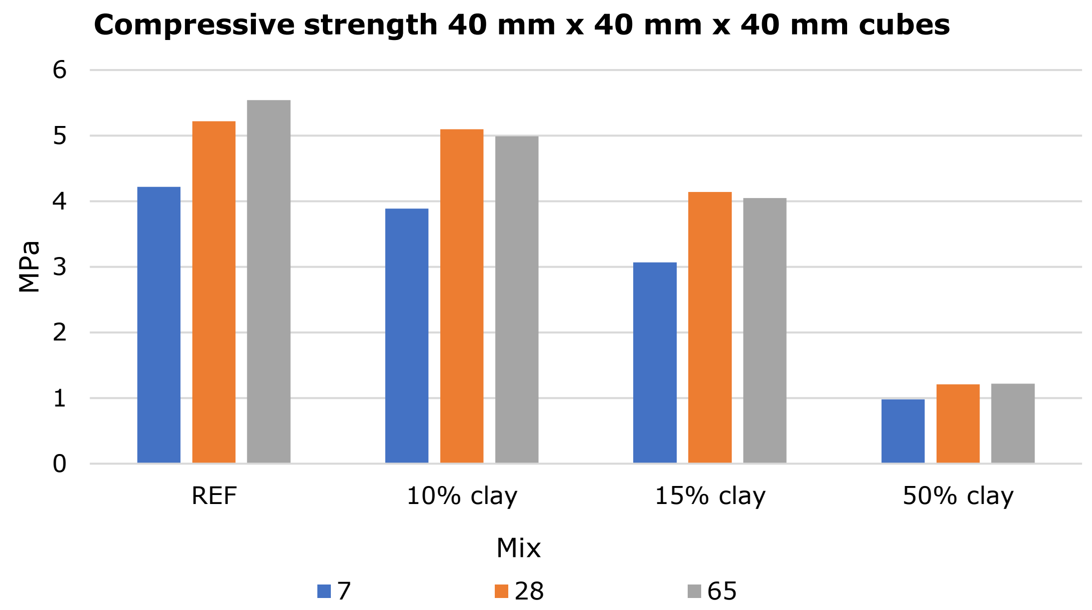

Figure 4-4 Results form 40 mm x 40 mm x 40 mm cube compressive strength tests of the different mixes after 7, 28 and 62 days.

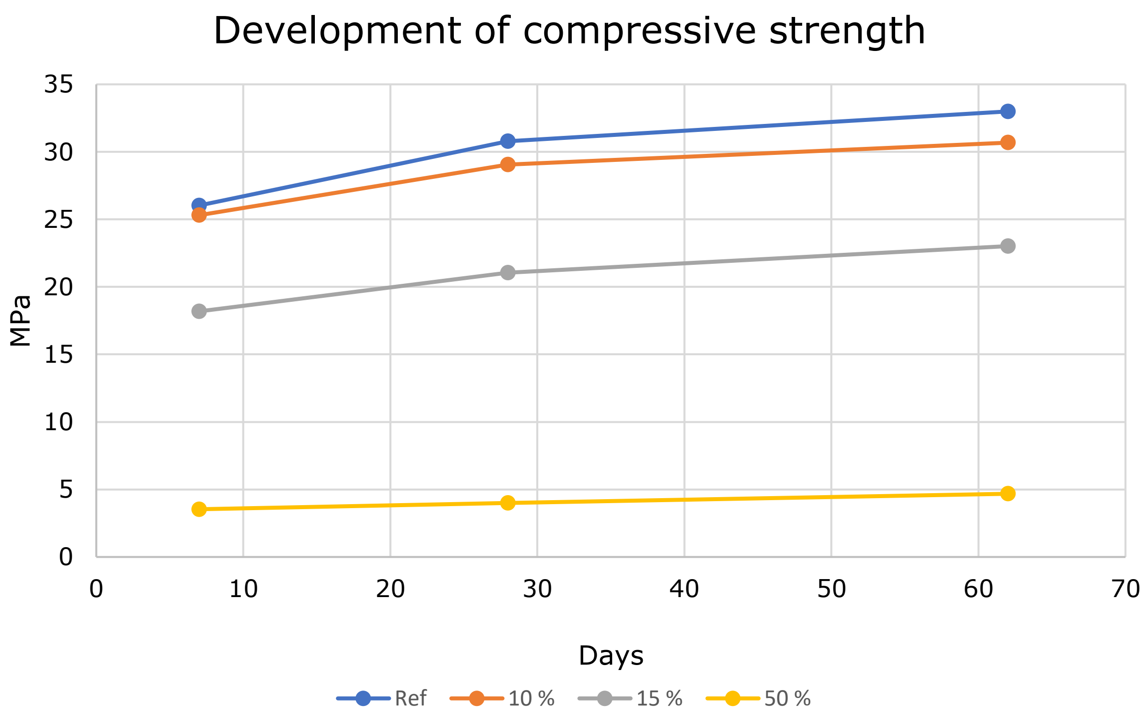

Figure 4-5 Development of compressive strength with time. All mixtures increase in strength, having the highest compressive strength after 62 days.

4.3 Tensile strength

The key results from the 3 point flexural tests are presented in Figure 4-6 and 4-7. Complete results are given in appendix 1.

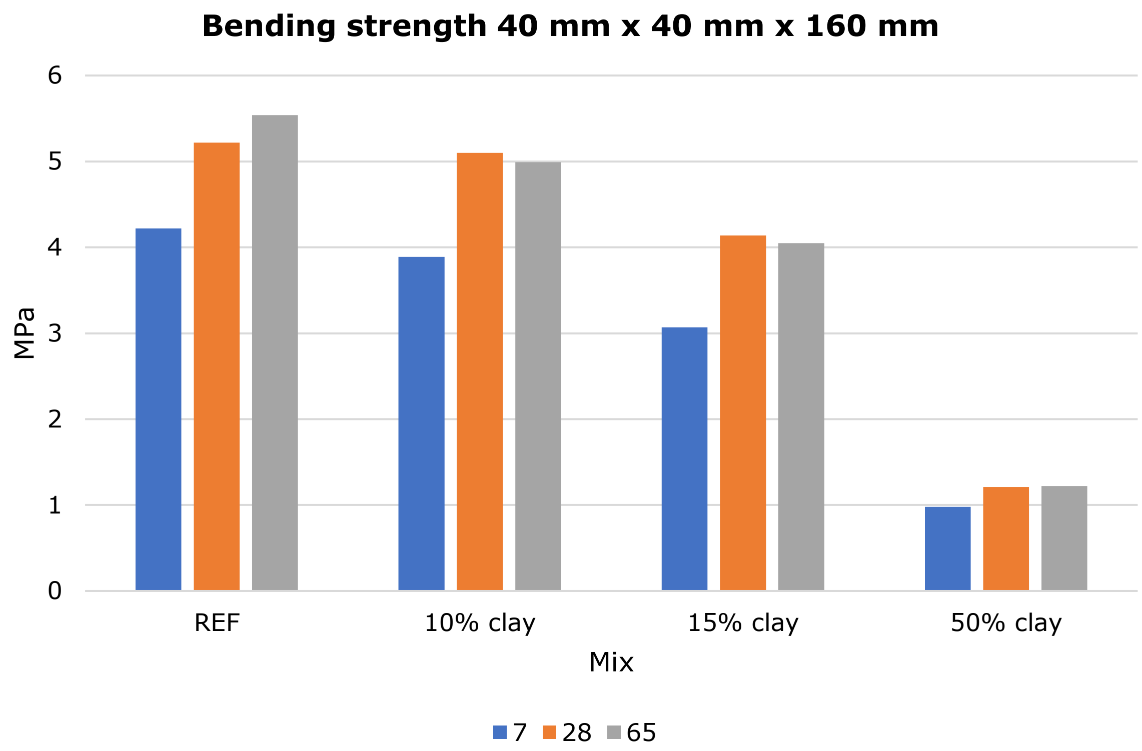

Figure 4-6 Results form 40 mm x 40 mm x 160 mm 3 point flexural tests of the different mixes after 7, 28 and 62 days.

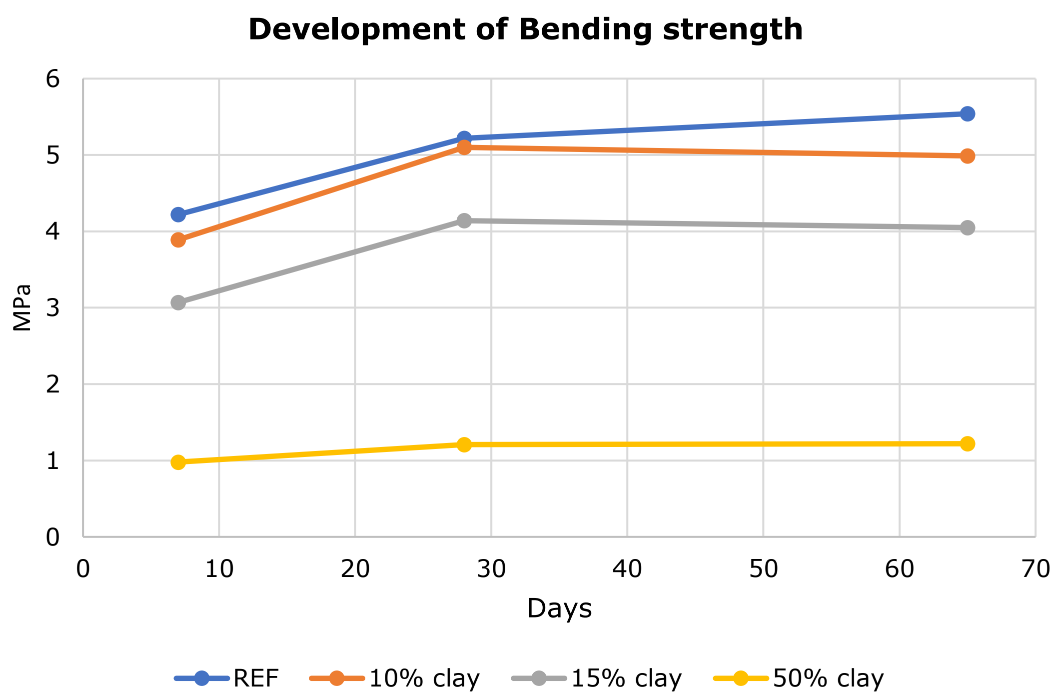

Figure 4-7 Development of compressive strength with time. All the mixes containing clay have some decrease in strength, having the highest bending strength after 28 days.

4.3.1 Additional tests

While the first tests indicate that replacing 10 % of the cement with clay give approximately a 10 % decreasing in strength after 28 days, the results from the additional tests show a bigger difference as presented in Figure 4-8 and Figure 4-9. The recipe of the mixes was not exactly similar, so the results cannot be directly compared. However, this indicate that only small variations lead to big changes. The bending strength decreased with approximately 20 % and the compressive strength with almost 40 % when the cement is replaced with 10 % clay.

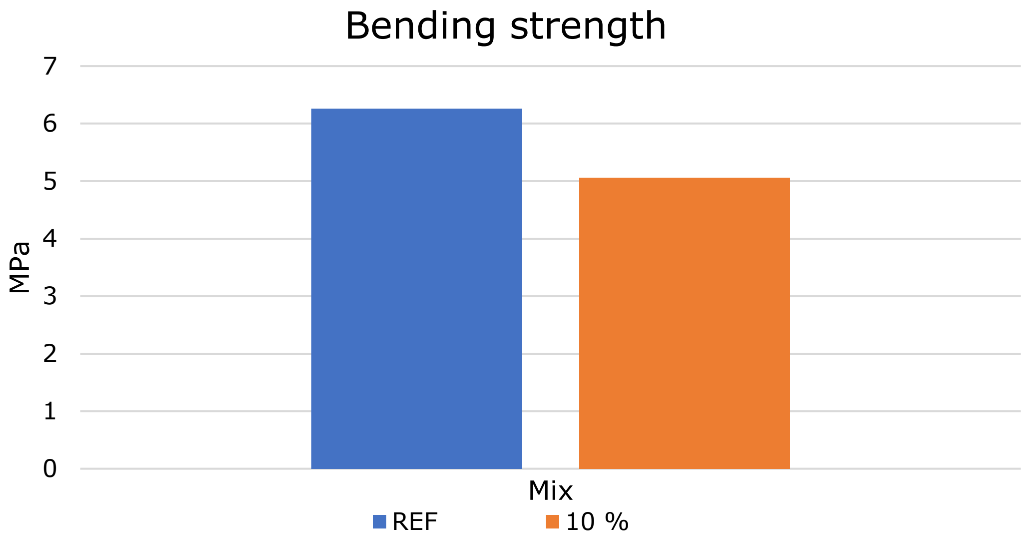

Figure 4-8 Bending strength after 30 days for the additional tests.

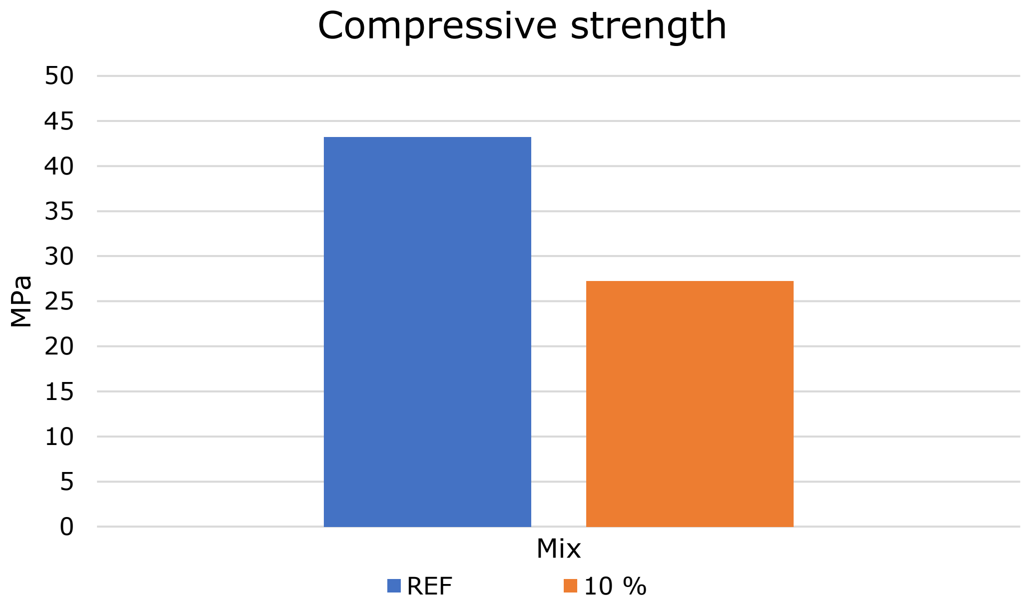

Figure 4-9 Compressive strength after 30 days for the additional tests

5 Field work

5.1 Future buildings

The demand for new buildings in Nepal is high, and drastically increased after the earthquake as a consequence of the major damages. Today, there is a shortage of both larger scale structures and smaller buildings.

An increased trend is that people are moving to the urban areas which create the need of more housing units. Traditionally, no tall buildings were to be found in the cities, as it was considered inappropriate and disrespectful to build taller than the temples. However, the increase in population in the urban areas has made it necessary to build taller units. These days, buildings with 3-8 stories are common, and even buildings with up to 12 stories are relatively normal to observe. In the cities it is common that big developers construct large buildings used for housing, and the poorer parts of the population rent one room for their entire family. Therefore, the slum areas are small compared to many other countries with similar economy. In addition to buildings used for housing, the urbanization has led to construction of new shopping centers, schools, offices, etc. Since the size of the buildings increases, the design process gets more complex, and many requirements need to be fulfilled. This makes only a small number of materials suitable for use in the structures if the safety of the building shall be guaranteed.

In the rural areas a shortage of schools, hospitals, and houses are a major problem, and there is a great need for better public buildings. In these areas few major developers find it profitable to build, and it is then the people living in the specific areas that usually construct the buildings. Most houses are small. Hospitals, schools, and other community buildings have barely more than two stories. For smaller buildings the same requirements do not apply as for larger buildings. Therefore, a wider range of materials can be used. In these cases, it is urgently needed to find affordable construction methods where local raw materials can be used, in addition to providing the people with the necessary knowledge of building work. This will make future constructions more sustainable.

5.2 Design codes

From conversations during the field study, it appears that earthquake is the main focus when designing new buildings. This is also reflected in the NBC, where almost all design principles are based on earthquake resistance. When the country was hit by an earthquake in 1988, the process of creating the NBCs started. Henry Degenkolb, a noted earthquake engineer, was quoted in the NBCs to illustrate why these guidelines were made [33]:

> *"…Conversely, if we start-off with a good configuration and reasonable framing system, even a poor engineer can't harm its ultimate performance too much."*

As a result, design principles that need to be followed to ensure a safe structure and good seismic resistance, are presented and detailed described in the different NBCs. Unlike in Norway, several specific solutions as dimensions for columns, beams and slabs are provided in the standard. In addition, specification of types and amount of reinforcement and how it can be added in common structure types are described.

Furthermore, recommendations for arrangement of the structural system are detailed described concerning:

- Structural simplicity
- Uniformity
- Symmetry
- Redundance
- Adequate lateral resistance and stiffness
- Diaphragm action
- Adequate foundation

These recommendations for the structural system apply for all type of structures independent of material. What seems to be one of the most important recommendations is to keep the structures simple and symmetrical, preferably symmetry in both directions. The is justified by the assertion that these buildings have better seismic performance. Symmetry leads to reduction in the ductility demand in the structural members which do not respond strongly in a torsion mode. In addition, a symmetric structure responds more predictable compared to more complex design.

Limited state method has to be used for design of structures. The structure shall be designed to withstand a dead load (DL) and live load (LL) combined with load factors as given in equation 5-1. In addition, it is necessary to consider the effect of the load from earthquake (E). For parallel systems equation 5.2 applies, where λ = 0,6 for storage facilities and $\lambda = 0{,}3$ for other structures.

$$eq. 7.1\ )\quad 1{,}5DL + 1{,}2LL$$

$$eq. 7.2\ )\quad DL + \lambda LL + E,$$

For non- parallel system, the lateral load resisting elements may be oriented in several different directions, and it cannot be assumed that all the load is in the direction of the element. To simplify, it is designed for the entire earthquake load in one direction, in addition to adding 30 % of the load in the other direction. These load combinations are used when designing structures, and for some type of design pre-accepted solutions are given in the standard. Further, the design procedures differ somewhat from the ones in Norway, among other things, it seems like material factors are not used, and the characteristic strength is used in the calculations. However, the material utilized is tested before and during construction to ensure that the strength of the material is the same as the strength accounted for in the calculations.

As mentioned in chapter 2, guidelines and rules for earthen constructions are limited to one building code, covering earthquake resistance for all earthen materials. Even though all materials are not covered in the NBCs, it needs approval by the Government to be used. After the earthquake in 2015 the Government started accepting new materials, and in 2017 CSEB was approved. Rammed earth, on the other hand, has been an accepted construction method for centuries. In general, these types of buildings are smaller and never constructed with more than 2,5 stories. Less requirements need to be fulfilled, and it is common to use standard solutions. Sometimes the developers also utilize building codes from other countries and books. For example, Ramro architect uses a building code from New Zealand and the book *Building with earth* when designing rammed earth structures.

The standards clearly state in the rules and pre-accepted solutions how it is desired that things should be done, which is reflected in the design of newer buildings, both finished and those under construction. Most of them are symmetrical, and a similar type of design recurs. For detailed information about design req, all standards are given in the Nepali government website [33]. However, from conversation with locals, it seems like several years passed without the NBC was used in practice. Several entrepreneurs, many unskilled, continued building without following the guidelines for years. First after the major earthquake in 2015 changes took place. The Government started to renew some of the building codes, and the routines for following up projects became stricter. In addition, it seemed like people started taken building design more seriously as a consequent of wanting safe housing and limitation of devastations from a new earthquake. After this, the impression is that almost all entrepreneurs follow the requirements given, and less shortcuts are taken.

5.3 Materials

5.3.1 Concrete structures

In the urban areas concrete is used in small and large scale projects. For larger concrete structures a civil engineer is always involved in the design process to ensure that the requirements are fulfilled.

The design is similar regardless of usage area, following the recommendations and solutions given in the NBCs. The structural system consists of columns, beams, and slabs. Using shear walls is not common, but it can be observed in some buildings. Instead, the columns are relatively massive, and combined with the beams it works as a moment resistance frame.

- The columns are normally placed 1-1,5 m from the facades so that a balcony or roof extension can be built
- Columns are typically placed with a center to center distance of 5-7 m.
- Secondary beams are used to strengthen the slab, if necessary, as illustrated in Figure 5-2.

One common solution for the structural system in the buildings is presented in Figure 5-1. In appendix 3 one drawing of the design is presented.

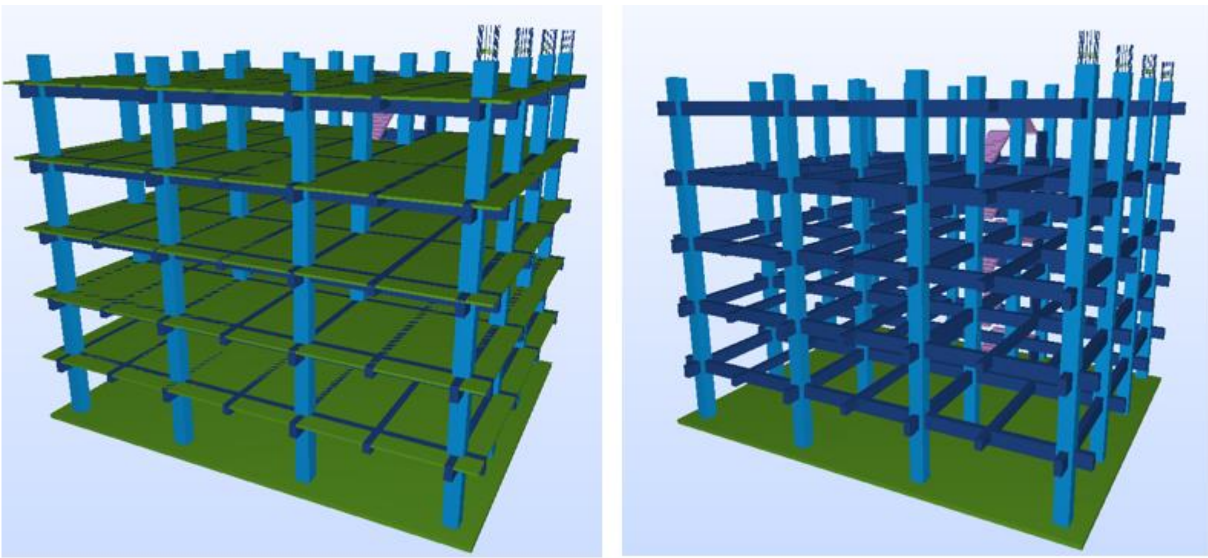

Figure 5-1 Typical design, demonstrated with and without the slab.

Figure 5-2 The left pictures shows a connection between the column and beams. The right pictures show a secondary beam meeting one of the main beams.

It is common to use concrete with lower strength than in Norway. For larger structures concrete with a cube compressive strength of 20- 25 MPa is commonly used in Nepal. While in smaller projects concrete with even less compressive strength is used. Depending on the wanted strength they utilize nominal mixes as presented in Chapter 2.2.1. Table 5-1 shows the key information for the different concrete elements used in the buildings visited during the field study. The values do vary to some extent, depending on the project, usually though in the same range.

Table 5-1 Information about the structural elements

Structural element	Dimension in mm	Nominal mix	Reinforcement
Columns	300x300 to 600x600	M25	ø12, ø16
Beams		M20	ø12
Secondary beams		M20	ø12
Slab	Most commonly 100	M20	ø12

The nominal mixes give the ratios in volume, and cement bags are typically used to measure the amount of the different components. On the construction sites they were very focused on this ratio. The w/cm ratio, on the other hand, did not seem to be that important. To make the concrete easy to work with, it was not uncommon that some extra water was added to the mix. However, the civil engineers were aware of this short cut. Therefore, they were taking this problem into account, and one of the engineers said that he for example always calculated for a w/cm of 0,6, although a w/cm of 0,4-0,5 was given in the recipe that was used on the construction site.

Mixing is then done by using a mixer, as illustrated to the left in Figure 5-3, or by using a shovel and a rope, as illustrated to the right. It is preferred by the developers that the mixer is used, but at higher floors hand mixing is sometimes preferred by the workers as it is difficult to displace the concrete from the ground floor to higher floors without a crane.

Figure 5-3 Alternatives for mixing of concrete at the construction site. To the left is the mixer shown. Right picture illustrate how they sometimes mix the concrete

Both the concrete itself and the reinforcement are expensive, especially the latter. Reinforced concrete is therefore normally used only for load-bearing elements. Partitions and facades are built in traditional red masonry bricks. According to NBC 201 the bricks should be of *"...standard rectangular shape, burnt red, hand-formed or machine-made, and of crushing strength not less than 3.5 N/mm²"*. The inner walls though are often covered with other materials and the surface appearance is not as important. Therefore, different types of bricks are utilized for inner walls and the facade (see Figure 5-4).

Figure 5-4 Masonry used in the inner walls to the left. The picture to the right show a finished facade with red bricks.

Several buildings can be observed with columns with protruding reinforcement on the top floor which work as a temporary roof. This is illustrated in Figure 5-1 and in the left picture in Figure 5-2. This solution is relatively common, and it is a result of the developers' plans for enlargement at a later stage when they can afford it. In many cases, it takes several years before the construction process resume. Nearby one of the construction sites visited during the field study, the extension of the building started after a ten year break. Sometimes the construction process never resumes, and instead of a roof many buildings are left with a top floor with columns and protruding reinforcement for its entire service life.

5.3.2 Rammed earth

Rammed earth is an ancient building technique, traditionally used in many countries all over the world. Today, the method is not very widespread in Nepal, but the material has gained popularity the latest years. The material is utilized in structural walls in buildings with 1 to 2,5 stories. Rammed earth can be used both with and without cement as a stabilizer. However, for taller buildings it is necessary to use cement to obtain the required strength and the necessary approvals from the Government. Rammed earth cannot withstand much water, and the construction technique is most suitable for areas with little rain. When used in areas with heavy rainfalls, rammed earth walls are typically combined with a roof that covers parts of the wall. This increases the durability of the structure.

Generally, for smaller buildings local soil from nearby area is moist and used directy in the walls. For larger buildings the different components are separeted in fines, sand, and gravel and mixed after a given recipe. At the construction site, visited in Budanilkantha, gravel and sand were used from nearby areas. However, the clay was transported from areas 50-60 km away since the clay in Kathmandu does not have good enough quality. This mix consisted of the following amount of the different componenets given by volume:

- 30-35 % clay
- 50-55 % sand, can be substituted with crushed stone.
- 10-15% gravel.
- In addition, 5-10 wt. % cement was added.

In Figure 5-5 a sieve curve for the soil mix used in a building project in Budanilkantha is illusrated. In this proejct big parts of the sand were substitued with crushed stone. This is advantageous considering that sand is one of the raw materials that are limited in the country.

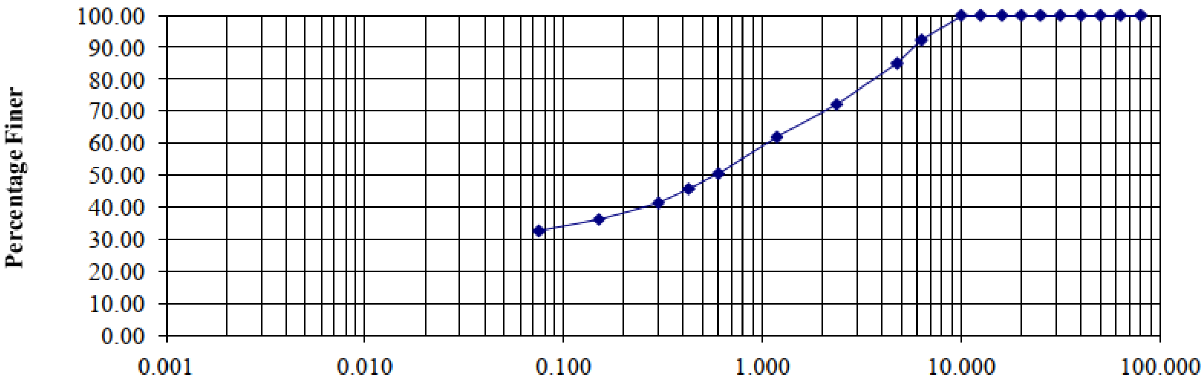

Figure 5-5 Sieve curve used in a project in Budanilkantha, Nepal. The soil consist of 33 % fines, mostly clay. 52 % sand and crushed stones and 15 % gravel. From analyses conducted by Ramro Mato architect firm, provided my RM Pandey.

The strength of the material varies depending on several factors. The properties of the soil and the water content are the most important. Especially for larger buildings, it is therefore necessary to conduct tests when soil from new areas is used in order to guarantee that the strength requirements are fulfilled. Further, it is important that the average compressive strength is higher than the required compressive strength since the quality of the soil often varies. Compressive tests done before starting on the project in Budanilkantha illusrate this with an avrage compressive strenght of 8,4 N/mm2 and a standard deviation of 3,6. The test emphasizes the importance of testing the material properties both before and during construction to ensure adequate quality of the material.

Date of test	Dimension (In mm)	Weight (N)	Unit weight (kN/m^3)	Breaking load (N)	Comp. strength (N/mm^2)
02.04.2021	155x155x155	86,3	23,17	227292	9,46
14.04.2021	155x155x155	87,9	23,6	134900	5,61
14.04.2021	155x155x155	88,5	23,77	243800	10,15

Figure 5-6 Compressive tests before construction started in Budanilkantha. The strength varies significantly between the tests. From analyses conducted by Ramro Mato architect firm, provided my RM Pandey.

Building with rammed earth is more complicated than bricks and concrete. Therefore, it is important that the construction workers have adequate knowledge about the method. The construction technique also requires a good number of working hours compared to building with concrete or masonry. The routine for building the walls is done as presented in Chapter 2.4.5. Some pictures from the building process are presented in Figure 5-7. First, the clay is dried in the sun and crushed to fines in a machine. Then the different components are mixed together, often by hand. In some cases, a mixer is used to improve the quality of the material. Some water is added bit by bit until optimum moisture content is achieved. This is tested by using the drop test as described in Chapter 2.4.5. Then the framework is built, and the earth is added in layers, being compressed by using rammers. Next step is to remove the framework and fill the holes with earth to obtain a nice surface. The walls are then left untreated for a period before some sort of natural or chemical treatment are added to the surface to improve the durability.

Figure 5-7 Construction of rammed earth walls. To the left, the machine is used to crush the clay. In the middle, a mixture of clay, sand, gravel, and cement are worked up. To the right, a framework is presented.

In larger buildings it is common to use reinforcement in order to increase the strength of the walls. It is common to combine a "plastic reinforcement mesh", as illustrated in Figure 5-8, with some regular reinfså orcement.

Figure 5-8 Picture to the left shows two construction workers removing the framework. The middle picture shows a construction worker filling the holes with earth. In the picture to the right the plastic used as reinforcement, is shown.

The red clay used in the material gives the walls a warm expression that a lot of people appreciate. The material is sometimes mixed with different colored clays to give a specific architectural impression. The pictures in Figure 5-9 illustrate some different alternatives. The walls are not painted or added any materials that hide the bearing structure.

Figure 5-9 Different rammed earth walls.

For larger projects the cost of building with rammed earth is comparable with the price of building with concrete. In many cases more expensive. In addition, concrete structures often increase in value while this is not the case when using rammed earth. Today, the developers choosing to use rammed earth in bigger projects does not do it because of economic reasons. Advantages that are highlighted and seems to be important for the ones building with rammed earth are:

- In general, use of earthen materials are positive from an environmental perspective.
- Rammed earth has a distinctive layered appearance and is often described as an attractive material from an architectural perspective.
- The material regulates humidity and temperature well and provides a good indoor climate. For example, the developer in the project in Budanilkantha chose to use rammed earth instead of having air-condition.

5.3.3 CSEB

CSEB is a relatively new building technique that was approved by the Nepali Government during the reconstruction of the country after the Gorkha earthquake. The material is suitable for buildings where low cost and safety are a priority, and it is most popular in rural areas. The material opens up for more people to have access to their own safe home. *Build up Nepal* is one of the companies in the country working with this technology. The main focus of the business is to deliver affordable and earthquake resistance structures. In addition, they focus on environmentally friendly solutions and is at all times looking for alternatives that can help reduce the CO2 footprint.

CSEB is made by mixing soil, clay, and cement. In the latest years, they have also started producing an alternative block consisting of mining dust and cement. The two alternatives are illustrated in Figure 5-10. The mining dust was previously dumped in the river, but is now used in the blocks instead, which in itself is a good move. Use of mining dust provide bricks of uniform quality, while use of local sand and clay could have somewhat varying quality. However, both alternatives are of good enough quality to use in the structural elements in everything from small houses to 2-floors buildings. After the mix is compressed into earth blocks, by using a press as presented in Figure 5-10, the blocks then need to be stacked and cured for 21 days.

Figure 5-10 Left picture: CSEB with soil and mining dust. Right picture: One type of press. Several different alternatives exist, and they can produce from one to three earth blocks at a time .

Build up Nepal has contributed to the construction of thousands of buildings, and during 2022 they estimate that 5,000 buildings will be constructed using this technology. Two buildings constructed with their technology is presented in Figure 5-11. The company does not construct any of the buildings themselves. They sell the technology, the mechanical presses, and follow up local contractors so they can utilize these blocks when constructing new houses. The blocks can be produced locally, close to where they are to be used. Since the production can be done in rural areas, it make it possible for the workers to live at home. This involves that also people who may not have had the opportunity to travel far away to go to work for months can be employed.

Figure 5-11 Houses built using CSEB, picture from *Build up Nepal* [69].

5.4 Construction sites

The construction site and the conditions for the workers during construction are relatively equal regardless of the material used, some pictures from one of the construction sites are presented in Figure 5-12. The workers mix materials and work in slippers, sneakers or barefoot. In most cases they are not using any fall protection when working on high floors and the construction sites are generally characterized by poor safety.

Figure 5-12 Pictures from some of the construction sites. To the left is a scaffold built with bamboo. The middle and right picture is taken at one of the higher floors. The shafts and end of the slabs are not secured. The workers sit unsecured at 5^{th} floor. As the pictures illustrate the HSE should be improved.

At the rammed earth constructions, the workers had access to some safety equipment, and used it the time we were there. However, one of the engineers specified that this is something they typically do only when people are visiting the construction site. The challenges related to safety thus seem to be a combination of lack of access to equipment and that workers do not see the benefit of using the equipment.

The workers on the construction sites are hired on project basis. It is common that they work 12 hours a day 7 days a week. They earn between 800- 1200 Nepali rupees a day, which is equivalent to approximately 64-95 NOK a day. When working on a project the workers live at the construction sites away from their families. In the monsoon season, many developers do not want the construction work to be done, and the workers stay unemployed and without and income in this period. Usually, they travel home to their family and try to find work.

For the materials mixed on site, it is common to use old cement bags or alike to measure the right amount of the different components. Materials are mixed using volume ratios, and it is difficult to guarantee accurate mixtures. In addition, it is difficult to ensure that the right amount of water is added. Anyway, several uncertainties are associated with the construction process, especially mixing of the material, which in turn can lead to varying results. Using materials that are prefabricated can therefore give a more predictable result.

5.5 Preferences of the locals

It does not help to find alternative construction techniques if the people do not want to use it. Several factors are important when deciding which materials that should be used. Most important is that the material provides necessary strength, especially to resist an earthquake. Another significant aspect is that people often want what they are used to, and prefer well known materials that have proven to be of good quality.

All in all, the impression is that concrete is the preferred material, that everyone wants to build with. The material is associated with safety and prosperity. When people in the rural areas were about to rebuild their houses after the earthquake, different types of building materials were proposed. The cheapest alternatives were to use bamboo, stone or earth/ sandbags. However, people did not prefer to use these materials, as they thought using sandbags made their houses look like trenches, and bamboo or stone made the houses look poor. What the people wanted was concrete or masonry, as people in the cities had. Developing a product that is available everywhere and that looks familiar will therefore be essential.

5.6 Hypotheses and summary

Several factors are essential when deciding what material should be used in a structure. Table 6-1 overview of the advantages and disadvantages of using rammed earth and CSEB.

Table 5-2 Some advantageous and disadvantageous of using rammed earth and CSEB

	Advantageous	**Disadvantageous**
Rammed earth	- Thermal comfort and contribute to a comfortable and healthy indoor environment. - Environmental impact lower than for concrete - Architectural expression often considered unique and beautiful.	- Expensive compared to both concrete and CSEB - Varying quality depending on the soil, soil identification is necessary. - Not suitable for larger structures, limitations concerning spans and high.
CSEB	- Affordable, low-cost building technique - Contribute to growth in local business - Suitable for rural areas and give working possibilities nearby.	- size limitations, cannot be used to long spans or tall buildings. - soil identification is necessary, maybe not always possible.

The hypotheses formulated before travelling were used as a tool to ensure that essential information was collected. The result and the different assertions are presented below:

1. In urban areas, concrete is the most used material for all types of buildings.

Correct: Observations and talks with different consultants confirm that concrete is the most used material, at least in Kathmandu Valley. In the latest years, new constructions often have 6-12 stories, which reduce the number of suitable materials and making concrete even more popular.

2. Most people prefer concrete structures both in the rural and urban areas.

Correct: Observations and conversations with locals strongly indicate that concrete is the most popular material. In addition, burned bricks are preferred by many people. Especially a combination of the material is popular. After the earthquake, the process rebuilding the areas destroyed by the earthquake started, leading to new innovative and old long forgotten building techniques being tested. Among other companies, *Build up Nepal* tried to use environmentally friendly, easily available and cheap materials. However, it was almost impossible to persuade locals to use such materials even though they guaranteed that the buildings would have sufficient quality. This led to a survey being conducted in order to identify what material people preferred. The result was unanimous, and all 200 participants, living mainly in rural areas, preferred concrete and bricks. They wanted to use materials that the big developers use in the cities, and if they could choose freely concrete would have been their first choice.

3. Reinforcement is not always used even in the cases it is demanded.

Correct and incorrect: For ages, construction workers did not practice reinforcement engineering in order to avoid increase in the total costs. However, after the earthquake, reinforcement has become standard procedure. Of course, it cannot be 100 % guaranteed that the right amounts of reinforcement are carried out, but the routines are good, and it seems to be done correctly in almost all cases. All construction sites, both the one we visited and the one we just passed by, reinforcement work was done.

4. The introduction of new design codes has provided the country with the necessary knowledge to construct buildings of good quality, resulting in improved structures.

Correct and incorrect: Today the building codes are diligently used, but earlier there were no routines to check if the building codes were followed, and in most cases they were not. However, after the earthquake the regulations and follow-up routines became stricter, and as a result the quality of the buildings increased. Therefore, the focus on constructing buildings of good quality has increased drastically in the last few years. People do not want to lose their homes again, and today design standards are used, and most buildings are designed by structural engineers or by following standard solutions.

5. There are many unfinished buildings because of high costs, and people do not have the opportunity to finish the buildings.

Correct and incorrect: There are a lot of unfinished structures, but the unfinished buildings are from the beginning planned to be incomplete. In several places in Kathmandu Valley buildings can be observed with rebars sticking up, as shown in Figure 1. The buildings can stay like this for several years or throughout their entire service life. For example, one building near one of the construction sites visited, had just been restarted after a ten-year break. This is usually because the owner cannot afford to build as many floors as they want at once, so the top floor is prepared for further building when time comes; see pictures below.

Figure 5-13 Pictures of buildings with typical design, concrete and masonry bricks. The columns with protruding rebar make the building ready for extension at a later occasion.

6. Providing housing at an affordable price is challenging, especially in rural areas, since the access to raw materials is limited.

Considering that Nepal is one of the poorest countries in the world, finding affordable alternatives is crucial, and the price of the material is naturally an important factor when deciding what material that should be used. RC and concrete count same price range, but since RC is very popular, it is easier to sell it with a profit. CSEB is a low cost material. Therefore, from an economic perspective RC seems to be preferable over rammed earth and concrete if the size of the buildings allows for it.

7. Provide necessary raw materials in the rural areas are challenging.

Correct: Providing materials for buildings in rural areas is challenging, mainly due to the deficient infrastructures. For example, 20-40% of the bricks being transported up the Himalayas on very poor roads break on the way. Therefore, finding ways to utilize local resources in materials are essential.

8. Substitute parts of the cement with clay are most relevant for concrete buildings in urban areas.

Incorrect: Observations from the construction sites indicate that adding a new component to the mixing procedure on-site is not a good idea. It is important to keep the mixing as simple as possible to increase the probability that the required strength is obtained. One of the supposed advantages using unheated clay was that it could be used directly at the construction sites, which after the visits do not seem like the best idea considering all the uncertainties linked to the construction work.

However, using calcinated clay is a more promising alternative. Considering that calcination of the clay happen at a factory premixing calcinated clay and cement similar to how for example cement and fly ash are mixed in Norway could be an option. Then, it is easy to keep control over the amount added and the quality of the clay used. In addition, by premixing so the cement and calcinated clay are packed in the same bag, it could easily be used in rural areas as regular cement. Therefore, this alternative could be an option both for urban and rural areas.

6 Discussion

6.1 Clay as a substitution for cement

6.1.1 Key elements

Independent of unheated clay or calcinated clay shall be used some elements need to be fulfilled before the sustainability of the material should be discussed, see Figure 6-1.

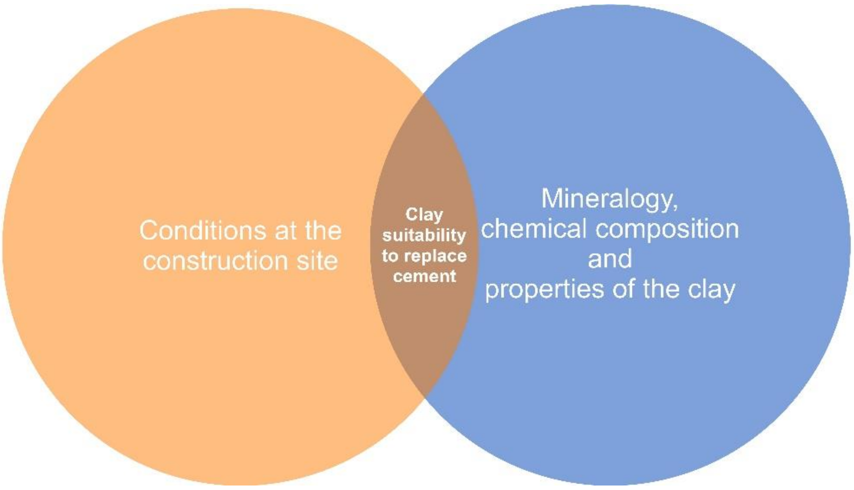

Figure 6-1 Important factors to consider independent of whether the clay is calcinated or not.

The concrete utilized in Nepal has relatively low strength, and the nominal mixes M20 and M25 are typically used in larger projects, first being the minimum requirement given in the NBC. In smaller buildings, concrete with even lower strength is utilized. Therefore, if clay should be used as SCM, it is decisive that the strength does not decrease much.

The mineralogy and chemical composition of clay varies, influencing the reactivity of the clay. Preferably, clay with high kaolinite content should be utilized. However, other clay minerals like montmorillonite, mica, and illite also have pozzolanic behavior. When it comes to chemical composition, the total amount of silica, alumina, and iron should be greater than 70 %, and the total percentage of these components indicates the quality and suitability as a SCM. Considering the importance of the mineralogy and chemical composition, clay cannot be used as SCM without performing multiple tests in advance.

In addition to strength properties, it became clear from the construction sites visits the importance of the workability. If the concrete recipe results in a mix difficult to work with extra water is typically added altering the w/cm ratio and the properties of the mix. Therefore, it is important that adding clay not negatively influence the workability.

In addition to factors connected directly to the material external factors also need to be considered. The number of uncertainties connected to the construction work is already high, adding one more uncertainty factor, in terms of adding one more component, should not be done without some adjustment to the working process, making it possible to ensure that the correct amount is added. Therefore, if clay shall be added directly at the construction sites, changes in the building practice of today are necessary.

6.1.2 Unheated clay

From a sustainable development perspective, using unheated clay to replace cement would be ideal considering being more environmentally friendly and low cost than calcined clay.

Observation during the experimental tests shows that the mix's workability decreases drastically as the amount of clay increases. For the blend with 50 % clay, the w/cm needed to exceed 1, not even then, the workability was good, and the mix was almost impossible to work with. The same applied to the other mixes containing clay. However, this can possibly be altered by using admixtures, and it is an obstacle that probably would have been relatively easy to solve.

More critical is that using unheated clay as SCM decreases the strength drastically. From the experimental tests, as illustrated in Figure 6-2, the compressive and tensile strength decreases with an increased amount of clay, and substituting more than 10 % of the cement is inconvenient. These findings seem to be adequate and in accordance with the information in the literature, where other case studies on the topic show similar results.

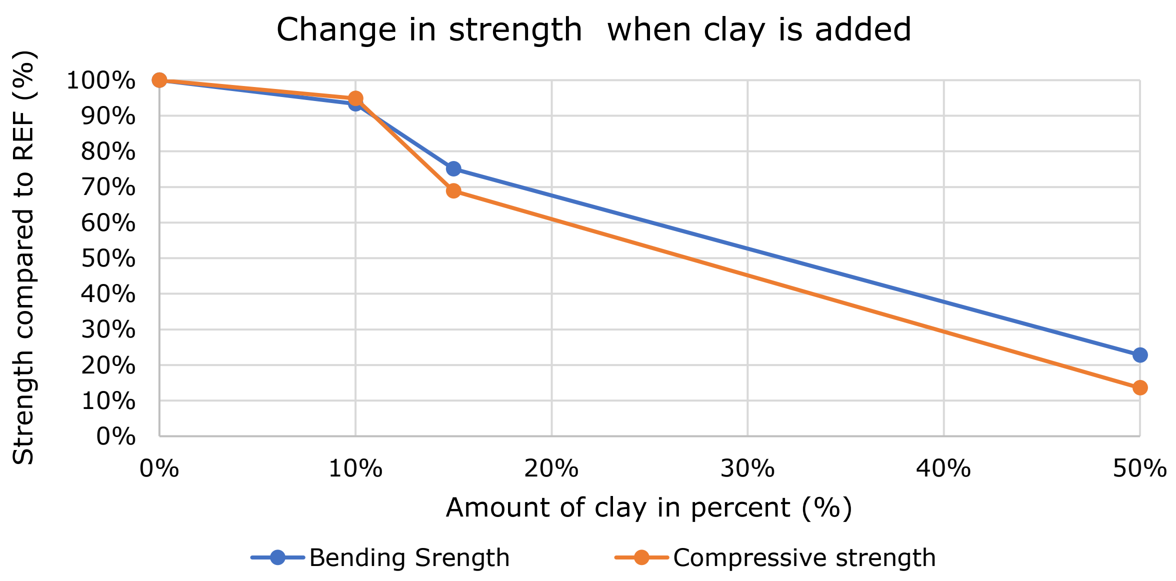

Figure 6-2 Replacing 10 %, 15 % and 50 % of the cement, the reduction is approximately 10 %, 30 % and 85 %, respectively, compared to the reference.

The significant change in strength between the mix containing 10 % and 15 % clay is alarming since it causes a considerable reduction, only increasing the amount of clay with a small percentage. While 50 % of the cement is substituted, the tensile and compressive strength is only 22,8 % and 13,6 % of the reference mix, meaning that it is possible to obtain the same strength using earth-based materials.

All mixes gain some additional strength over time, and the results show that the blend with 50 % clay had the highest percentage increase in strength, as presented in Figure 6-3. However, the strength was low in the first place, and the total strength is still considerably lower than the reference mix. This fits well with the fact that the reactivity in the clay is slower than for cement and that it thus takes longer before the strength develops. This complies with the findings from the literature review, where it is concluded that when using unheated clay, the reactions were too slow and did not give any positive contribution to early-age strength, which is necessary.

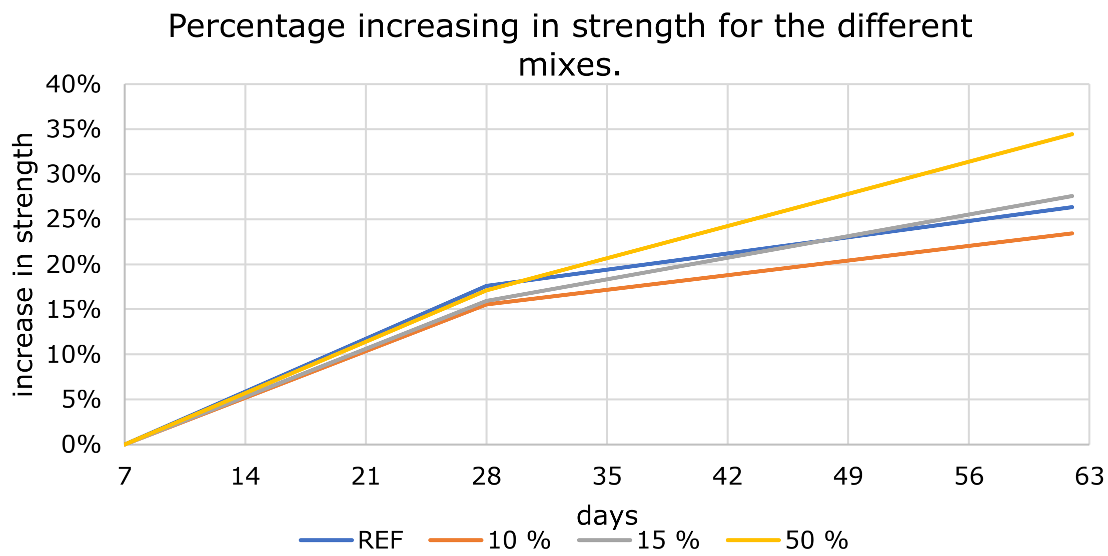

Figure 6-3 The mix containing 50 % clay has the highest increase. The REF mix has the highest increase in strength between 7 and 28 days.

From the tests substituting 10 % of the clay could potentially be possible. However, bearing in mind the results from the additional tests replacing even 10 % or less of the cement with unheated clay seems problematic. As presented in table x, the tests show almost 40 % and 20 % reduction in compressive strength and tensile strength, respectively, when the clay is added. Considering that these mixes differ from the original mixes, the results cannot be directly compared with the original tests. The three changes from the first mixes are described in Chapter 3.3.9. However, considering such minor alteration influencing the results, using unheated clay as SCM seems problematic. Especially considering the situation and the routines at the construction sites make it challenging to guarantee that the right amount of clay is added. Therefore, clay cannot be used without being tested regularly, and both the mineralogy and chemical composition should be known before the clay is utilized. If the clay is mixed directly into the concrete mix without being tested, it is impossible to guarantee sufficient quality.

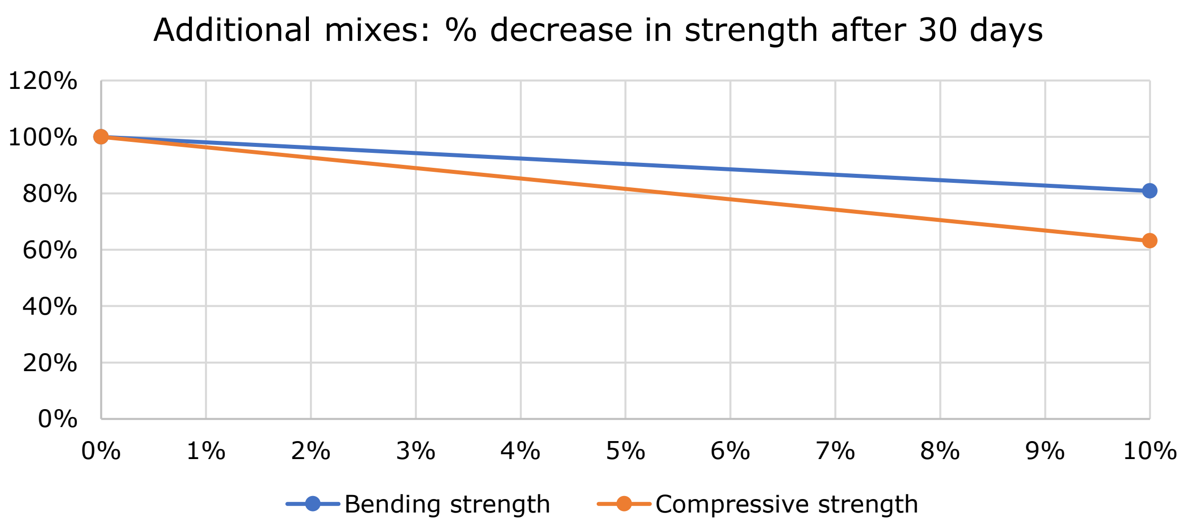

Figure 6-4 The mix containing 10 % only has 80 % of the tensile strength and 63 % of the compressive strength compared to the reference mix.

Initially, it was hoped that clay could be used directly from the ground it was taken. However, the need for testing immediately made adding clay more complicated and not as easy as first foreseen. Much of the purpose using untreated clay, initially intended as an easy alternative using clay directly from a nearby area in the concrete mix, disappears.

6.1.3 Calcinated clay

Evidence concerning calcined clay as a substitution for cement is promising since the calcination destroys the clay minerals' crystal structure and transforms it into a very reactive structure. Therefore, it can be a suitable SCM, and it is possible to obtain the same strength and durability as when using OPC. Better durability has even been observed. Also, using LC3 is a promising alternative making it possible to decrease the amount of OPC even more.

As pointed out in Chapter 6.1.1. if calcinated clay should be used, the mineralogy and chemical composition is essential and must be determined before calcination. The total content of silica, alumina and iron oxide, together with the burning temperature and duration of burning, affects the physical properties of the clay used as pozzolan in concrete. Therefore, the quality of the clay varies. Considering that the pozzolanic behavior increases when calcinated, a wider range of clay consisting of different clay minerals could be used. The method makes it possible to use low grade clay, which makes the method suitable for use in Nepal.

In addition to having plenty of raw material, Nepal also has cement fabrics that are not fully utilized, and only 50% capacity is utilized. In addition several new cement factories are planned for in the future. This opens up for the use of calcined clay, which can be calcinated at the existing cement plants. Resulting in little to no capital intensive is required. Another advantage if cement and clay are produced at the same place is that the two can premixes, similar to cement and fly ash in Norway. Then the uncertainty of adding one extra component to the mixing process at the construction sites disappears, and the ratio between cement and clay is guaranteed to be correct.

Calcinated clay seems to have several advantages. However, some challenges and uncertainties are associated with this alternative, and especially three limitations are identified associated with using calcinated clay as SCM. First, as mentioned previously in the discussion, the workability increases due to the increased water demand when clay is utilized. The thermal treatment reduces the water demand usually associated with the presence of clay. However, it is still necessary to add more water compared to OPC. This is the easiest obstacle considering that this can be solved by adding a superplasticizer. Some limitations for the amount of cement occur for structures in exposure conditions where carbonation induced steel corrosion can be an issue. From the literature review, it seems like no more than 30 % of the cement should be replaced with clay. The third limitation is that even though the alternative has gained popularity in the latest years, it is still several aspects with the alternative that need to be examined. An increased number of projects are built using calcinated clay, but it is still not very common. Research regarding the subject is relatively new as far as the information obtained in the literature and the impression from the fieldwork using calcinated clay are not tested in Nepal at all. Therefore, several aspects still need to be investigated, and their suitability to be used in Nepal must be examined. Meaning that using calcinated clay is not likely to happen tomorrow. However it is an interesting alternative that can be utilized in the future with great probability.

Using calcinated clay contributes positively to making concrete a more sustainable building material. From the literature review, it is clear that even though the clay needs to be calcinated, the temperature is approximately half of what's necessary producing OPC. Therefore, CO2 emissions will be reduced. When using LC3, a blend of limestone and calcinated clay makes it possible to reduce the CO2 emission by up to 40 %.

Considering that the same or similar factories as the cement ones, using calcinated clay does not provide any additional social advantages compared to using OPC, except for the positive consequences the reduced emission gives. Economically clay is a cheap raw material, cheaper than cement, which means that using clay potentially can reduce the total cost of the concrete. However, this is difficult to say with clarity and cannot be guaranteed, and it needs to be looked deeper into.

Al in all, everything found in the literature implies that it is possible to replace parts of the cement with clay. However, the exact amount needs to be closer investigated and depends on several factors, as mentioned. And several elements need to be figured out before calcinated clay can be used in practice. However, worldwide, several projects are already built using calcinated clay, and it is an alternative that should be further investigated as an alternative in Nepal.

6.2 Building with earth

6.2.1 Suitability and availability

At the beginning of the project, one of the thought advantages of building with earth-based materials was that the soil could be used directly anywhere without further investigation. However, not all soil types are suitable for earth-based materials. From the literature review, it is clear that when using earth based materials, an analysis of the soil must be made so that the right quality can be guaranteed. It is, therefore, necessary to do some tests before using the material. Nevertheless, rammed earth and CSEB are construction methods opening up for using local materials, but one extra step of testing the quality needs to be added.

6.2.2 Strength

First of all, the structural requirements for the load-bearing components need to be fulfilled. The population growth in the country, especially in the urban areas, is increasing while the land areas available are limited. Therefore, many larger-scale buildings are being constructed, and today, buildings with 6-12 stories are common. For these types of buildings, several requirements to the material's properties apply, and concrete seems to be the best alternative for the load-bearing components.

However, several projects are also planned with 1-2 floors, and approximately 90 % of all new buildings have a size of 50 m2 or smaller. Especially in the rural areas, most new buildings are of a smaller scale. It is easier to fulfil the given requirements in these cases, and a more comprehensive range of materials can be used. Without further investigations and structural analysis for the specific structure, a rule of thumb is that earth-based materials can be used for buildings with two and a half floors.

6.2.3 Durability

Considering that buildings often are used for generations without being maintained, durability is decisive. Today, both rammed earth and CSEB can be used and obtain the necessary durability, as the earth-based materials have improved in the latest year.

However, rammed earth may have a limitation in the area with a lot of rainfall, and a roof with sufficient overhang must be used to prevent heavy rainfall from hitting the wall directly. On the other hand, CSEB buildings can withstand heavy rainfall, snowfall, and frost without damage and much maintenance. Nevertheless, both materials seem to have sufficient durability to be used in the evaluated areas as long as the design and work are done correctly.

6.2.4 Workability

Workability of the material influences the finished results, and it is decisive that the production of the bricks or wall is done correctly, if not, the results will be uneven, and the quality and strength of the construction will vary greatly. Factors at the construction sites that influence the properties of the finished construction element are the mixing and water content. If the material is challenging to mix, the cement and aggregates will typically separate from each other, resulting in an inhomogeneous mix. Also, it is necessary that the mix easily can be compacted in the formwork to obtain the necessary strength and density.

As mentioned in chapter 2, it is decided to extend the term to cover how easy the materials are to work with. Compared to concrete, Rammed earth is a more complicated and time-consuming construction technique and requires that the workers have some knowledge about the method. However, the fact that the method is time-consuming does not negatively influence the workers since they are paid for the time they use.

CSEB are made using steel presses, then the blocks are used in the buildings in a similar way as burned bricks. Feedback from some workers has even been that the CSEB is too easy to build with, resulting in the working time decreases, which some workers consider a disadvantage since they are paid for the time they work.

It is possible to obtain the necessary workability and obtain the necessary using rammed earth and CSEB, as long as the proper adoptions are done at the production and construction sites.

6.2.5 Sustainability

The sustainable development concept is based on three fundamental pillars: social, economic and environmental. All three must be fulfilled to achieve a sustainable future.

Most researchers agree that earth-based materials are better than concrete from an environmental perspective. The literature indicates that earth-based materials generally have a lower environmental impact than concrete. Working towards reducing CO2 emission, replacing concrete structures with CSEB or rammed earth will have positive effect. When building in rural areas, buildings with earth-based material make it possible to use local soil, reducing the CO2 emission, even more, considering that only cement needs to be transported to the construction location.

When it comes to the cost of the materials, CSEB is the cheapest alternative making it available for the poorer part of the population. On the other hand, rammed earth is expensive, and from an economic perspective, concrete would be preferred over rammed earth.

From conversations during the fieldwork, the impression is that the working conditions and salaries seem similar regardless of which material is used. Considering the similarities between concrete and rammed earth, RE doesn’t have any particular advantages from a social perspective. CSEB, on the other hand, has a positive impact. The production of the blocks gives opportunities to establish businesses and provides work in rural areas. This involves that people who may not have had the opportunity to travel far away to go to work for months, can be employed. In addition, women and men are employed.

When introducing new or reintroducing traditional construction methods, it is decisive that the locals accept the building technique. Otherwise, despite the quality of the material, it will not be used. Most people prefer concrete and masonry since the materials are associated with safety and prosperity. Therefore, finding a way to increase knowledge and make earth-based materials wanted is essential. CSEB, having many similarities with masonry bricks, is a good alternative that seems to be approved by the inhabitants.

6.3 Other findings and further work

During the project, other aspects that could improve the sustainability of the construction industry in Nepal have been brought to light. It is worth mentioning that the construction industry has improved significantly, especially after the earthquake. Wanting to prevent a similar outcome if a new earthquake hits in combination with the introduction of building codes and stricter routines have resulted in better quality and safer buildings.

Nevertheless, several things in the construction industry can be improved. Organizing the construction sites is one relatively simple measure that could result in more sustainable building practices. Several uncertainties are connected to the mixing. The two main areas are connected to the amount of water added, and the quality of the mixing to get a homogeneous mix. Safety measures are conducted to ensure sufficient capacity. Today, it is common for the engineers to calculate using a higher w/cm than the one given in the material recipe. Good routines and investing in some additional equipment for mixing the concrete would be a simple measure to reduce the cement content as it would be possible to calculate the w/cm used. Working with optimization of the concrete mix and see if the ratio between cement, fine- and coarse aggregates could lead to a better final result.

If calcinated clay is to be used in Nepal, several aspects need to be examined closer. First, the mineralogy and chemical composition of the available clay in the country should be examined, and areas with suitable clays must be found. Then, how much of the cement that can be substituted with this clay should be investigated.

The structural limitations should be investigated for rammed earth structures, and if the material could be used in taller buildings is of interest. Rammed earth buildings with up to eight floors exist worldwide, but the seismic activity in the country may be a limitation. Also, restrictions related to water resistance should then be examined.

7 Conclusion

In this project, two alternatives have been examined in working towards a more sustainable construction practice by decreasing the use of cement. From the investigations it is possible to conclude that substituting parts of the cement with calcinated clay is appropriate and sustainable. However, unheated clay is proven to be unsuitable to use as a replacement for cement. The research also makes it possible to conclude that earth-based materials are suitable to use instead of concrete in some cases. Still, not all, and for usage in many constructions, concrete seems to be the only acceptable option.

Through a review of the literature and experimental tests, unheated clay suitability to replace parts of the cement was investigated. Evidence from the test results shows that the strength of the concrete decreases drastically when increasing the unheated clay content. Furthermore, all the uncertainties in conjunction with the mixing process at the construction sites and the clay needing to be tested to guarantee sufficient quality, make the alternative more complicated than expected. Altogether, combining the results from the lab work, and observations done in the field with the reviewed literature, gives a strong indication that unheated clay is not suitable to replace parts of the cement.

The evidence concerning calcined clay as a substitution for cement is promising. The calcination destroys the crystal structure of the clay minerals and transforms it into a very reactive structure. Therefore, calcinated clay alone or in combination with limestone seems to be suitable SCM. Furthermore, when calcinated clay is used correctly, it can obtain the same strength, and its durability is often improved. The combination of the easy access in Nepal and the low costs of clay, this option is an interesting alternative that should be further investigated.

The second alternative being examined was the earth-based materials rammed earth and CSEB suitability to replace concrete. The earth-based materials seem to be an equally good alternative as concrete for many constructions, at the same time as CO2 emission is reduced. However, every material shows advantages and disadvantages, and some types of structures are more or less suitable. It is essential to mention that concrete has had a positive effect on the development in the country, and it is a material with several advantages. Thinking that the use of concrete should stop entirely, does not seem realistic. In some types of structures, when the size of the building exceeds 2,5 stories, it is impossible to obtain the given requirements when using rammed earth or CSEB. In many cases concrete will still be the best option.

However, for smaller buildings with less than 2,5 floors, both CSEB and rammed earth can be used. CSEB seems to be the best option being both a low-cost material suitable for rural areas and distributed to local businesses and giving work to inhabitants nearby where they live. Rammed earth has more limitations, being more expensive and a somewhat more complicated construction technique. However, rammed earth is an instinctive architectural expression with great potential. However, being a costly material, it is unsuitable for rural areas and the cases where low costs are essential.

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Appendices

Appendix 1: Material recipe and results from the experimental tests

Appendix 2: Material recipe and results from the additional experimental tests

Appendix 3: Architectural drawing from a concrete structure in Kathmandu, Nepal.

Appendix 1

Appendix 1

Mix	Phase	Materials	Quantity	Densitiy	Volume	Volume phase	Total volume
REF	Matrix	cement	356,8	3080	115,8441558	297	980
		clay		2850	-		
		water	178,4	1000	178,4		
		sand*	7,9	2650	2,981132075		
	Particle	Sand	602,7	2650	227,4339623	683	
		Gravel	1229,4	2700	455,3333333		
10 %	Matrix	cement	307,95	3080	99,98276596	325	980
		clay	34,25	2850	12,0169797		
		water	209,88	1000	209,8772255		
		sand*	7,60	2650	2,867948885		
	Particle	Sand	575,58	2650	217,2017491	655	
		Gravel	1182,72	2700	438,0459144		
15 %	Matrix	cement	262,38	3080	85,1883867	388	980
		clay	46,32	2850	16,25362914		
		water	284,01	1000	284,0120427		
		sand*	6,87	2650	2,59089143		
	Particle	Sand	519,98	2650	196,2190307	592	
		Gravel	1068,47	2700	395,7286028		
50 %	Matrix	cement	143,68	3080	46,64868902	423	980
		clay	143,68	2850	50,41332007		
		water	323,20	1000	323,2017759		
		sand*	6,46	2650	2,439196934		
	Particle	Sand	489,54	2650	184,7305729	557	
		Gravel	1005,91	2700	372,5590288		

1. total volume phase will not be equal 1000 since it is considered that approximately 2 % air content.
2. water content in the sand is tested and added water is included this amount of moisture.

Comment on the calculation of the amounts: The amount of clay was substituted on the weight basis of the original mix resulting in a higher total volume. Then, the recipe was adapted to apply to 1m3 concrete.

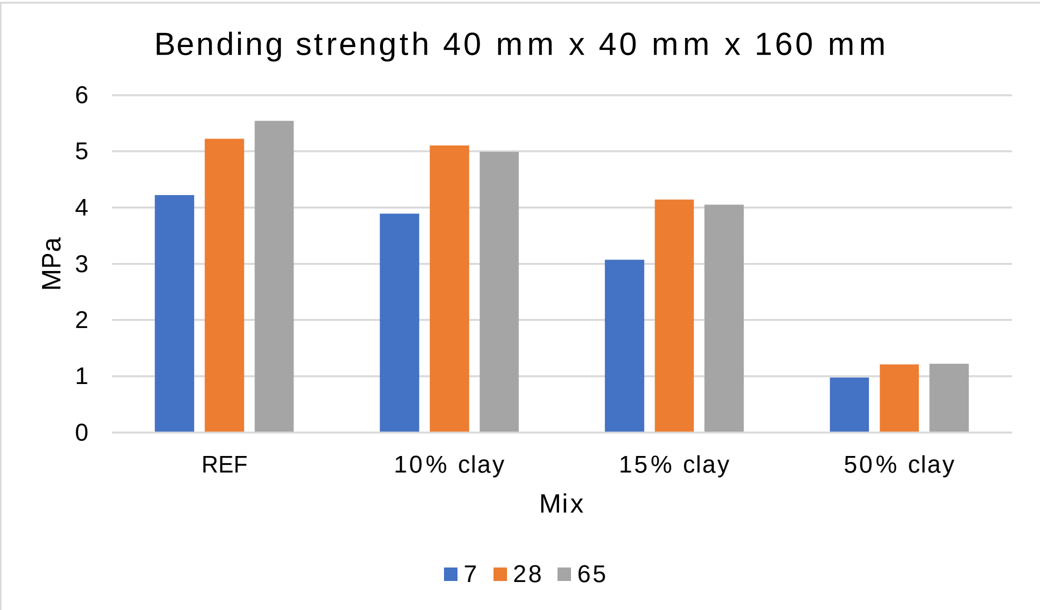
Appendix 1

RESULTS BENDING STRENGTH

Bending strength after 7 days *3 point flexural test, tested 31.03 and 01.04*			
mix	Fm (kN)	σm	% of ref
Ref	1,8	4,22	100,00 %
10 %	1,7	3,89	92,18 %
15 %	1,3	3,07	72,75 %
50 %	1,8	0,98	23,22 %

Bending strength after 28 days *3 point flexural test, tested 21.04 and 22.04*			
mix	Fm	σm	% of ref
Ref	1,8	5,22	100,00 %
10 %	1,7	5,10	97,70 %
15 %	1,3	4,14	79,31 %
50 %	1,8	1,21	23,18 %

Bending strength after 62 days *3 point flexural test, tested 24.05 and 25.05*			
mix	Fm	σm	% of ref
Ref	1,8	5,54	100,00 %
10 %	1,7	4,99	90,07 %
15 %	1,3	4,05	73,10 %
50 %	1,8	1,22	22,02 %



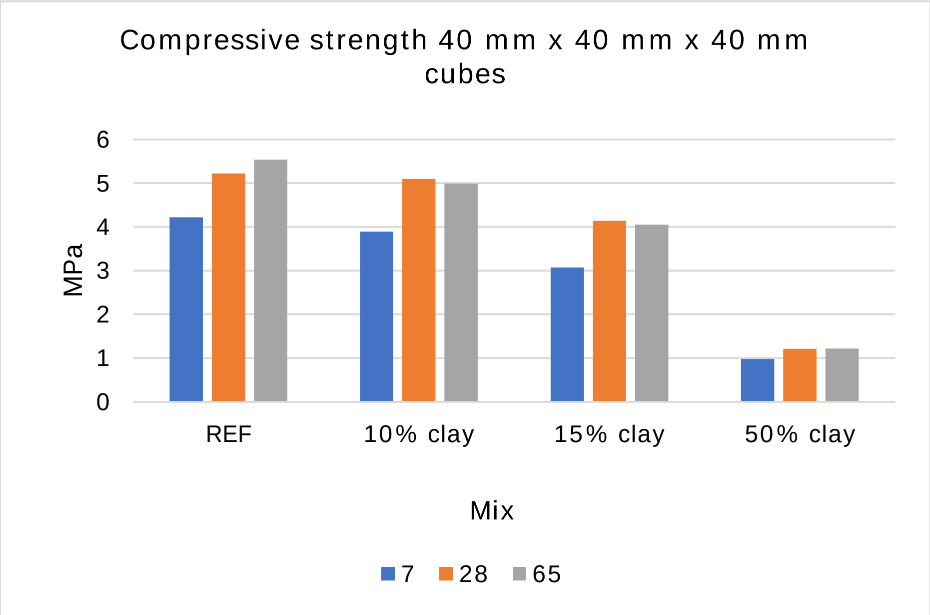
Appendix 1

RESULTS COMPRESSIVE STRENGTH 40 mm x 40 mm x 40 mm cubes

Compressive strength after 7 days *cube test, tested 31.03 and 01.04*				
mix	Fm	σm	avrage	% of ref.
Ref	40,9	25,54	26,03	100,00 %
Ref	42,4	26,52		
10 %	40,8	25,47	25,31	97,23 %
10 %	40,2	25,15		
15 %	29,1	18,17	18,19	69,88 %
15 %	29,1	18,21		
50 %	6,1	3,83	3,54	13,58 %
50 %	5,2	3,24		

Compressive strength after 7 days *cube test, tested 21.04 and 22.04*				
mix	Fm	σm	avrage	% of ref.
Ref	49,1	30,66	30,795	100,00 %
Ref	49,5	30,93		
10 %	46	28,77	29,065	94,38 %
10 %	47	29,36		
15 %	34,4	21,44	21,05	68,36 %
15 %	33,1	20,66		
50 %	6,1	3,83	4,00	12,97 %
50 %	6,7	4,16		

Compressive strength after 7 days *cube test, tested 24.05 and 25.05*				
mix	Fm	σm	avrage	% of ref.
Ref	53,3	33,3	32,995	100,00 %
Ref	52,3	32,69		
10 %	48,9	30,57	30,68	92,98 %
10 %	49,3	30,79		
15 %	38,2	23,89	23,02	68,42 %
15 %	35,4	22,15		
50 %	7,7	4,8	4,68	14,18 %
50 %	7,3	4,56		



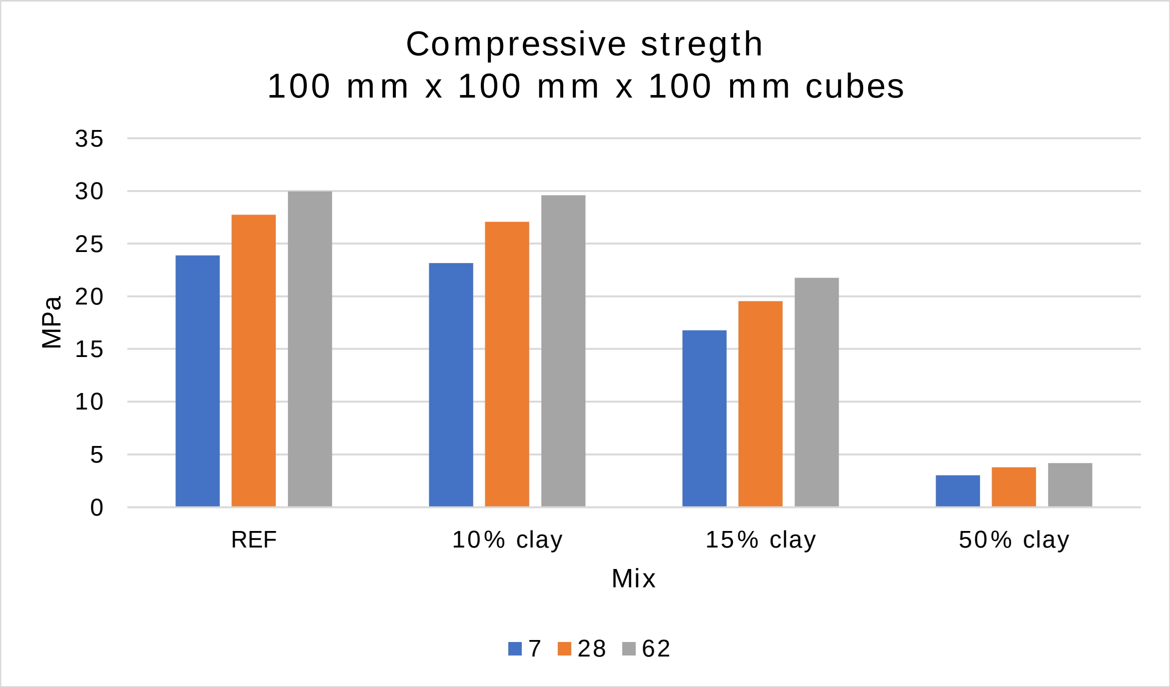
Appendix 1

RESULTS COMPRESSIVE STRENGTH 100 mm x 100 mm x 100 mm cubes

compressive strength after 7 days *cube test, tested 31.03 and 01.04*			
mix	Fm	σm	% of ref
Ref	238,72	23,87	100,00 %
10 %	231,52	23,15	96,98 %
15 %	167,82	16,78	70,30 %
50 %	30,13	3,01	12,61 %

compressive strength after 7 days *cube test, tested 21.04 and 22.04*			
mix	Fm	σm	% of ref
Ref	277,29	27,73	100,00 %
10 %	270,29	27,07	97,62 %
15 %	195,33	19,53	70,43 %
50 %	37,67	3,77	13,60 %

compressive strength after 62 days *cube test, tested 24.05 and 25.05*			
mix	Fm	σm	% of ref
Ref	299,62	29,96	100,00 %
10 %	296	29,6	98,80 %
15 %	1,3	21,75	72,60 %
50 %	41,7	4,17	13,92 %



Appendix 2

Appendix 2

Mix	Phase	Materials	Quantity	Densitiy	Volume	Volume phase	Total volume
REF	Matrix	cement	440,21	3080	135,584915	373	980
		clay		2850	0		
		water	248,29	1000	234,282994		
		sand*	11,22	2650	3,1575629		
	Particle	Sand	856,05	2650	240,895269	607	
		Gravel	1325,45	2700	366,079259		
10 %	Matrix	cement	320,74	3080	104,134937	321	980
		clay	35,64	2850	12,5043121		
		water	201,00	1000	201,001186		
		sand*	9,08	2650	3,42785116		
	Particle	Sand	693,02	2650	261,51597	659	
		Gravel	1073,02	2700	397,415744		

1. total volume phase will not be equal 1000 since it is considered that approximately 2 % air content.
2. water content in the sand is tested and added water is included this amount of moisture.

Comment on the calculation of the amounts:
The amount of clay was substituted on the weight basis of the original mix resulting in a higher total volume. Then, the recipe was adapted to apply to 1m3 concrete.

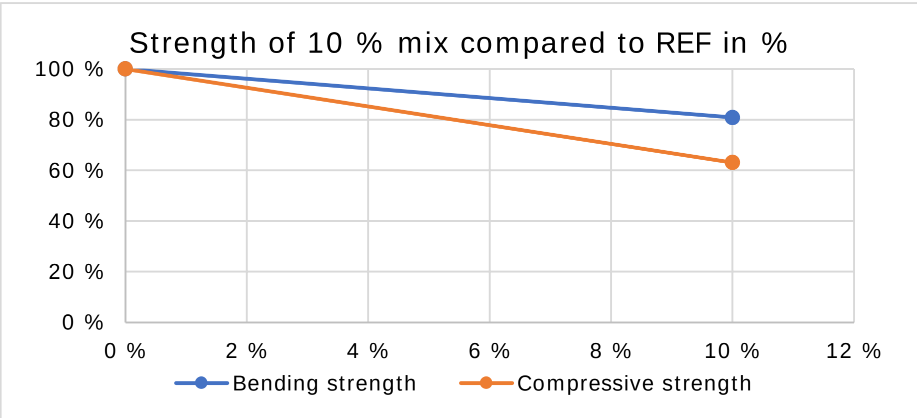
Appendix 2

Test of additinal mixes after 30 days

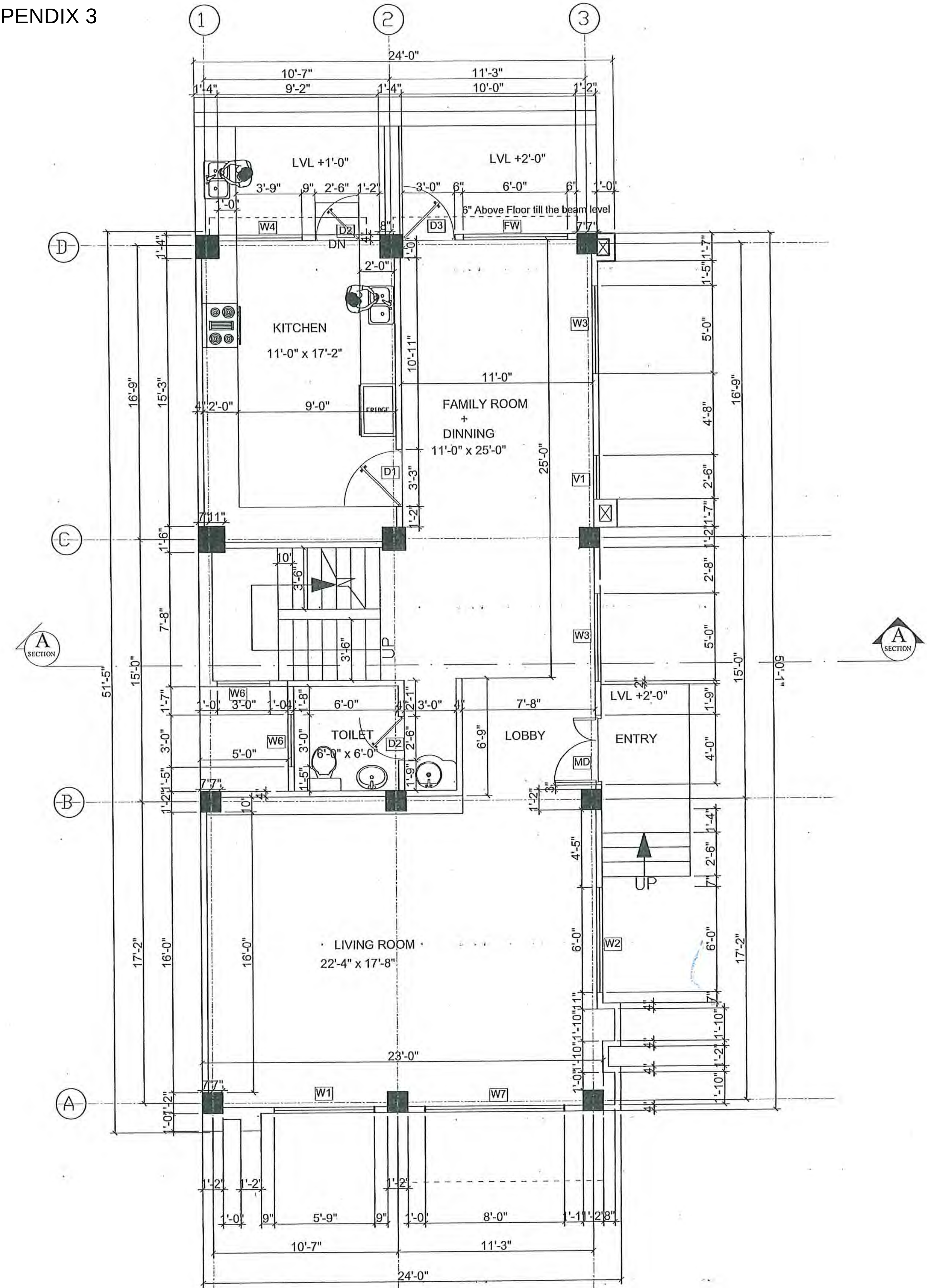
Bending strength 3 point flexural test					
mix	Fm	om	avrage	st.div	% loss
REF	2,8	6,6	6,25666667	0,36115555	100,00 %
	2,5	5,88			
	2,7	6,29			
10 %	2	4,63	5,0575	0,31826352	80,83 %
	2,2	5,31			
	2,3	5,29			
	2,1	5			

Compressive strength 40 mm x 40 mm x 40 mm cubes					
mix	Fm	om	avrage	st.div	% loss
REF	410,31	41,031	40,9776667	0,09586101	100,00 %
	410,35	41,035			
	408,67	40,867			
10 %	263,96	26,396	26,3486667	0,04158525	64,30 %
	263,18	26,318			
	263,32	26,332			

Compressive strength 40 mm x 40 mm x 40 mm cubes					
mix	Fm	om	avrage	st.div	% loss
REF	70,8	44,23	45,4966667	2,03650354	100,00 %
	75,1	46,94			
	73,2	45,73			
	73,5	45,95			
	67,5	42,2			
	76,7	47,93			
10 %	45,6	28,49	28,18125	1,64544772	61,94 %
	46,6	29,12			
	43,2	26,97			
	46,2	28,9			
	44,5	27,81			
	39,7	24,81			
	47,7	29,79			
	47,3	29,56			



APPENDIX 3



GROUND FLOOR PLAN

1147.92 square ft.

Scale=3":16'

Provided by Sangeeta Singh, Professor in Urban Planning and Deputy Director at the Centre for Disaster Studies at the Institute of Engineering at Tribhuvan University.

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