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Mohammadullah Hakim Ebrahimi

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**THÈSE POUR OBTENIR LE GRADE DE DOCTEUR
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**SUSTAINABLE EARTH CONSTRUCTION FOR AFFORDABLE
HOUSING IN KABUL**

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Le 01 décembre 2022

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RÉSUMÉ

Les techniques de construction modernes peuvent-elles répondre à l'immense programme de construction de logements sociaux dans la ville de Kaboul? L'Afghanistan souffre de décennies de guerre, ce qui a provoqué une migration massive de la population rurale vers les villes, où les afghans peuvent trouver une meilleure sécurité, des possibilités d'emploi et d'éducation pour leurs enfants. Kaboul, la capitale du pays, est l'une de ces villes qui, à l'origine, a été conçue pour 1,5 million de personnes et, où maintenant près de 5 millions de personnes vivent (Ebrahimi et al., 2022). Cette migration vers les villes est principalement due aux différentes guerres. À Kaboul, un changement démographique rapide se produit en 1979, lorsque la Russie attaque l'Afghanistan, puis en 2001, lorsque les États-Unis et les forces de la coalition arrivent dans le pays, de nombreux Afghans quittent alors leurs maisons dans les zones de guerre et déménagent vers Kaboul. Par conséquent, la population a augmenté rapidement, passant de 600 000 personnes en 1970 à 1 500 000 en 1980 et à 4 860 880 en 2019 (Kazimee, 1977) (Najimi, 2016) (CSO, 2019). Ces gens ont besoin d'un abri pour vivre, mais pour ce pays en développement, il s'avère vraiment difficile de fournir un logement à cette population déplacée. Le ministère du Développement Urbain et de l'Aménagement (2019) estime que 70 % des populations urbaines vivent dans les bidonvilles et une enquête de l'UNFPA (2015) montre même que ce chiffre grimpe à 72 %, ce qui, dans certaines régions, a entraîné une surpopulation, une faible qualité de vie et des écarts socioéconomiques importants entre les Afghans. Cependant, il reste beaucoup de gens qui n'ont pas accès au logement.

Cet afflux de personnes vers Kaboul et l'incapacité du gouvernement à leur fournir un logement ont provoqué le développement massif de colonies informelles. En 2004, une enquête de la Banque mondiale a montré que 80 % de la population de Kaboul vivait dans des bidonvilles, qui représentaient 69 % de la surface résidentielle totale et qui fournissaient un abri à 2 440 000 personnes (World Bank, 2006). 12 % de cette population vit sur les pentes des collines et des montagnes, sans infrastructures de base. Cette enquête est basée sur l'interprétation des images satellites Ikonos. Ces installations sauvages ne concernent pas uniquement Kaboul, toutes les grandes villes du pays souffrent de ce problème. Les politiques de logement de l'Afghanistan ont défini quelques étapes pour surmonter cette pénurie de logements, sur la base desquelles chaque année 41 704 logements doivent être construits. Malheureusement, le

gouvernement et le secteur privé ne peuvent en construire que 5 à 10 % chaque année (MUDL, 2019). Cette demande de logements pour la ville de Kaboul est estimée à 17 163 logements/an entre 2015-2019 et 18 090 logements/an entre 2020-2050 (UNFPA, 2015). L'incapacité du gouvernement en place, la corruption et le manque de moyens sont les principaux problèmes qui empêchent le gouvernement de fournir un toit à ces citoyens. La plupart de ceux qui vivent dans ces colonies informelles n'ont pas accès aux infrastructures de base, à l'eau, à l'assainissement et à la collecte des déchets. Au cours des vingt dernières années, de nombreux quartiers modernes se sont développés dans la ville de Kaboul. Entre 2002 et 2012, 85 quartiers ont été construits (Ekleel Abdulraqib et Junichiro Asano, 2014). Les colonies informelles et ces nouveaux quartiers ont radicalement changé la vision de Kaboul au point de ne plus reconnaître la ville.

Dans la ville de Kaboul, traditionnellement, la majorité des bâtiments sont construits avec des briques de terre crue ou en bauge. Cependant, ces nouveaux quartiers et la plupart des bidonvilles utilisent des matériaux modernes tels que des briques de terre cuite, des structures en béton armé et des façades en verre. Ils ne sont ni isolés ni raccordés aux systèmes de chauffage central et consomment donc beaucoup d'énergie, ce qui constitue un problème pour les Afghans à faible revenu. Avec de très nombreuses variations, les maisons à cour créent un tissu urbain typique des villes afghanes traditionnelles à forte densité (Kazimee, 2006). Actuellement, plus de 95 % des Afghans vivent dans des maisons à cour (Sharifzai et coll., 2016). Avec ces nouvelles formes d'urbanisme dans la ville de Kaboul, la valeur du logement se détériore, alors que nous pouvons trouver une valeur culturelle et sociale systématique dans le logement traditionnel afghan. Contredisant de nombreux pays en développement ayant une expérience de la vie sociale incertaine et fragmentée, le modèle traditionnel de logement de l'Afghanistan a un moyen d'organisation physique, spéciale et sociale avec la culture afghane (Donald J Watts, 1983). Par conséquent, l'architecture traditionnelle de la terre devrait jouer un rôle dans l'urbanisation rapide de la ville de Kaboul. *L'objectif de ces travaux de recherche est de proposer un modèle réaliste pour la construction de logements sociaux dans la ville de Kaboul en utilisant les techniques modernes de construction en terre.*

Pour cela, trois sites avec différents types de sol, un jaunâtre (Deh-Sabz), un blanchâtre (Arghandi), et un rougeâtre (Band-e-Ghazi) situés dans la province de Kaboul ont été

sélectionnés. Pour savoir si ces trois sols sont utilisables pour la construction en terre, leurs caractéristiques physiques telles que l'analyse par la diffraction aux rayons X, la texture, les propriétés hydrauliques, les limites d'Atterberg, l'essai Proctor et l'essai de limite de retrait linéaire ont été étudiées.

Pour les trois sols, les diffractogrammes présentent principalement de la calcite et du quartz. Nous avons effectué une séparation de la fraction inférieure à 2 μm afin de mettre en évidence la partie argileuse. Ces sols sont principalement composés de calcaire et de quartz, la présence de chlorite et de muscovite a été clairement observée. Le résultat de l'analyse granulométrique montre que la teneur en argile et en limon est très élevée pour les sols Deh-Sabz et Arghandi, 98,0 % et 93,7% respectivement. Pour le sol Band-e-Ghazi, ce pourcentage n'est que de 31,2 %. Avec un indice de plasticité compris entre 7,2 et 15,3, les trois sols sont qualifiés de légèrement plastiques. Pour les sols Deh-Sabz et Arghandi, la limite de liquidité est qualifiée de moyenne. Pour le sol Band-e-Ghazi, la limite de liquidité est qualifiée de faible. Des limites de liquidité supérieures à 50 % sont considérées comme élevées. Les normes AFNOR XP P13-901 (2001) et MOPT (2012) ont développé un polygone (basé sur les limites de liquidité et de plasticité du sol) pour déterminer si un sol convient pour la construction en terre. Selon ces définitions, les résultats des essais indiquent que les sols Deh-Sabz et Arghandi conviennent à la construction en terre, tandis que le sol Band-e-Ghazi est situé très près, mais à l'extérieur des limites du polygone. Ceci est dû à la faible limite de liquidité du sol Band-e-Ghazi. Cependant, ce résultat n'exclut pas ce sol parce que Accetta (Accetta, 2003) a montré qu'un sol en dehors du polygone pourrait être bon pour la construction en terre. Les résultats du test de retrait linéaire des trois sols sont bons.

Pour chacun de ces trois sols, trois formulations correspondant à trois types de brique de terre, l'adobe, le bloc de terre comprimé (BTC) et le bloc de terre stabilisée comprimé (BTSC) ont été mises au point. Pour la fabrication des blocs de terre stabilisée par compression, selon Steve Burroughs (2008) un bon sol pour la stabilisation au ciment devrait contenir entre 21 % et 35 % de limon et d'argile. La teneur en limon et en argile de Band-e-Ghazi se trouve dans cette gamme. Pour les sols Deh-Sabz et Arghandi, ce n'est pas le cas. Par conséquent, un mélange reconstitué a été préparé avec 75 % de sable de rivière (inférieur à 2 mm) et 25 % de sol. La teneur en ciment représente 10 % du mélange granulaire sec pour les sols Deh-Sabz et Arghandi et 9 % pour les sols Band-e-Ghazi. Les adobes ont été fabriqués à l'aide d'un moule

artisanal traditionnel mesurant 200mmx100mmx100mm. Pour les BTC et BTSC, le mélange humide a ensuite été compacté dans des moules de 300mmx155mmx100mm à l'aide d'une presse manuelle. Les adobes et les BTC ont été séchés à l'air, tandis que les BTSC ont subi une cure humide pendant trois semaines.

La résistance mécanique de ces trois types de brique a été testée à 7 et 28 jours. Pour ce qui est de la résistance à la flexion en 3 points, la procédure d'essai élaborée par l'ASTM C78 (2002) pour le béton a été suivie. Les résultats de cette analyse montrent que pour les sols Deh-Sabz et Arghandi, les BTC ont des résistances en flexion plus élevées à 7 jours et 28 jours, comparativement aux BTSC. On peut conclure que la stabilisation par le ciment n'influence pas vraiment la résistance en flexion des briques de terre compressée à un âge précoce. Au contraire, la présence de particules plus fines dans le sol semble davantage influencer la résistance en flexion des blocs. Par contre, pour le sol Band-e-Ghazi, la teneur en sable est identique pour les BTC et les BTSC. Les BTC fabriqués avec le sol Band-e-Ghazi ont presque les mêmes résistances flexion à 7 et 28 jours que les BTSC. Cependant, on remarque une forte augmentation (89 %) de la résistance en flexion des BTSC à 28 jours. Cette augmentation peut être attribuée à l'hydratation du ciment (Gernot Minke, 2006).

En ce qui concerne la résistance en compression, la procédure d'essai mise au point pour les briques de terre cuite par le British Standard Institute (1985) a été suivie. La résistance à la compression de chaque échantillon est calculée à partir de la charge maximale et de la section transversale brute d'origine. Quelle que soit la brique de terre considérée (adobe, bloc de terre compressée ou bloc de terre stabilisée compressée), les briques fabriquées avec le sol Deh-Sabz ont une meilleure résistance en compression que celles fabriquées avec les deux autres sols. De plus, quel que soit le sol considéré, la résistance à la compression des BTSC est supérieure à celle des BTC qui elle-même est supérieure à celle des adobes. Toutes les résistances en compression mesurées sont supérieures à 2 MPa, ce qui constitue un bon critère pour la construction en terre (Burroughs, 2008).

Deux types d'essais de durabilité ont été effectués (absorption d'eau et essai d'abrasion). Pour l'absorption d'eau, les essais 1 et 2 ont été effectués uniquement sur les BTC et l'essai 3 sur les BTC et les adobes. L'essai 4 a été effectué uniquement sur les BTSC.

1. l'absorption d'eau par capillarité a été évaluée par une méthodologie modifiée de Varum et al. (2007). Les BTC ont été coupés en deux et laissés dans l'eau pendant 6 heures. Les BTC ont été complètement érodés et il n'a pas été possible de mesurer l'absorption d'eau par capillarité.

2. La procédure d'essai élaborée pour les murs et cloisons en BTC, XP P 13-901 (2001), norme française a été choisie. Une face du bloc est immergée sur 5mm dans l'eau pendant 10 et 60 minutes et l'eau absorbée pendant ce temps est calculée. Une quantité importante des blocs s'est déposée au fond du réservoir et les briques se sont érodées en peu de temps.

3. La procédure d'essai pour la détermination de l'absorption d'eau par capillarité dans la norme EN 15801:2009 a été suivie. Les échantillons sont placés dans une boîte remplie d'eau au-dessus d'un coton, le pourcentage d'absorption d'eau par capillarité et la hauteur d'ascension capillaire ont été mesurés après 24 heures.

4. Pour l'absorption d'eau des BTSC, la procédure d'essai élaborée pour les briques de terre cuite par l'ASTM (2015) a été suivie. L'échantillon séché a été immergé dans de l'eau à 23 °C pendant 24 heures. Aucune érosion n'a été enregistrée.

Les résultats de l'essai d'absorption d'eau sur les briques non stabilisées confirment le peu de résistance à l'érosion hydrique de la terre crue, et ces éléments sont très peu résistants face au contact direct avec l'eau. Ils se désintègrent après quelques minutes. Par contre, ce n'est pas le cas des BTSC, pour lesquels aucune érosion n'a été enregistrée lorsqu'ils ont été placés pendant 24 heures dans l'eau.

Le test d'abrasion a été effectué selon la procédure d'essai standard développée pour les blocs de terre compressée, NF XP X 13-901. L'objectif de l'essai est de soumettre le bloc à un frottement effectué à l'aide d'une brosse métallique de 25 mm de largeur chargée avec un poids de 3 kg. Les résultats de l'essai du coefficient d'abrasion pour les BTC fabriqués à partir des sols Deh-sabz et Arghandi confirment que les briques ont une résistance élevée à l'abrasion (10,5 et 8,2 cm²/g) respectivement.

Les propriétés thermiques des briques ont été mesurées par une méthode d'analyse dynamique avec un appareil ISOMET modèle 2104. Il s'agit d'un instrument de mesure portable doté de sondes de surface et d'aiguilles pour la mesure directe des propriétés thermo-physiques d'une large gamme de matériaux isotropes. La sonde de surface a

besoin d'une surface plane d'au moins 60 mm de diamètre, l'épaisseur minimale requise est de 10 à 15 mm. Les briques de terre Arghandi ont la conductivité thermique la plus faible tandis que les briques de terre Deh-Sabz ont la conductivité thermique la plus élevée, en particulier pour les adobes. La conductivité thermique moyenne des briques de terre Deh-Sabz est 20 % plus élevée que celle des briques de terre Argandhi et 24 fois plus élevée que la conductivité thermique de la laine de verre.

Les propriétés physiques des adobes, BTC et BTSC fabriqués avec trois sols différents de la région de Kaboul (Arghandi, Band-e-Ghazi et Deh-Sabz) ont été comparées pour sélectionner la meilleure brique. Les résultats suivants ont été obtenus :

- Compte tenu des problèmes environnementaux, la stabilisation de la terre avec du ciment Portland n'est pas efficace, ni en termes mécaniques ni en termes environnementaux. L'utilisation d'une grande quantité de ciment ne provoque qu'une faible augmentation de la résistance en compression.

- Quel que soit le sol étudié, la résistance en compression sèche des blocs de terre compressée est généralement supérieure à celle des adobes, tandis que la conductivité thermique des deux types de brique est assez similaire. Cette augmentation significative est de 81 % pour le sol Arghandi, de 67 % pour le sol Band-e-Ghazi et de 109 % pour le sol Deh-Sabz. Cela montre que la technique la plus appropriée pour la production de briques de terre dans la ville de Kaboul est l'utilisation d'une presse.

- Si l'on considère les trois sols, la résistance à la compression sèche des BTC Band-e-Ghazi est 31 % plus faible que celle des BTC Deh-Sabz et 14 % plus faible que celle des BTC Arghandi. En raison de sa faible résistance à la compression, ce sol ne sera pas choisi. Conclure pour les deux autres sols n'est pas facile car pour le sol Deh-Sabz la résistance à la compression sèche est de 24 % supérieure à celle d'Arghandi mais la conductivité thermique est de 16 % supérieure à celle d'Arghandi. Compte tenu de la valeur de la conductivité thermique qui ne permet pas de classer les blocs de terre comprimée dans la famille des matériaux isolants, le sol Deh-Sabz peut être choisi comme le sol le plus approprié pour la construction de logements sociaux en terre à Kaboul.

L'objectif des expériences sur le mortier est de trouver le bon mélange qui sera utilisé pour lier les briques et comme enduit intérieur. Une grille de mélange avec différents taux de sol, sable et eau selon le guide brique de terre crue (Brique de terre crue, 2018)

a été élaborée à partir du sol Deh-sabz pour trouver les mélanges qui ne présentent pas de fissure après séchage. Quatre mélanges n'ont pas fissuré, et ils ont été analysés pour évaluer leur consistance, deux d'entre eux présentaient une consistance correcte pour la mise en oeuvre et ont été choisis pour effectuer d'autres analyses. Les essais de résistance en flexion, en compression et à la cohésion ont permis de sélectionner l'un des deux. Le mélange élaboré avec 1 kg de sol, 2 kg de sable de rivière et 0,75 kg d'eau est le meilleur mortier. Pour la résistance en flexion et en compression, la norme européenne (BS EN 196-1 : 2016) a été appliquée procédure d'essai développée pour la détermination de la résistance du ciment. Pour la résistance à la flexion 3 points, tous les éléments ont été testés après 28 jours. Pour déterminer la cohésion, la procédure décrite dans le guide brique de terre crue (Brique de terre crue, 2018) a été appliquée. Cinq échantillons de chaque mélange ont été fabriqués (5cmx4cmx1cm) et séchés à l'air libre. Après 28 jours de séchage, un poids de 2,5 kg a été suspendu à l'aide d'une sangle de botte souple sur le corps d'épreuve pendant 30 minutes. Les deux mélanges sélectionnés ont réussi ce test.

Deux études récentes sur l'optimisation de la performance thermique de murs composites en pisé proposent une méthode complète basée sur un indice d'évaluation. Cette méthode a permis d'élaborer une stratégie de conception pour le climat froid de Pékin en Chine en proposant une épaisseur de la paroi optimale pour la ville de Pékin (Yu, et al., 2022a; Yu, et al., 2022b). La même méthode a été utilisée pour déterminer l'épaisseur optimale des murs en blocs de terre comprimée pour la ville de Kaboul. Compte tenu du climat de Kaboul, l'épaisseur de paroi optimale (505mm), basée sur la performance thermique du mur a été sélectionnée. Cela comprend à l'épaisseur d'un et demi BTC et 30 mm d'enduit de terre/paille sur les deux côtés du mur.

En prenant en compte les matériaux locaux, l'architecture traditionnelle de la ville de Kaboul, la culture locale et les modèles existants pour les logements sociaux dans le pays, un nouveau modèle a été conçu. Il s'agit d'une maison à cour avec deux chambres côté sud, cuisine, toilette et des toilettes extérieures. Elle peut accueillir une famille afghane moyenne de 6 à 7 personnes (ONU-Habitat, 2017). Kaboul est située géographiquement dans la zone sismique C avec des tremblements de terre modérés (GUIDELINES 2003). Le modèle proposé doit donc être résistant aux tremblements de terre modérés. En conséquence, une forme rectangulaire simple avec des plans symétriques et des murs perpendiculaires a été choisie. Conformément à la ligne

directrice et aux propositions de Blondet et al. (Blondet, Garcia, Bretz 2003) pour des bâtiments stables sur le plan sismique, la maison comporte des fondations en pierres maçonnées, l'épaisseur des murs est proportionnelle à la longueur et à la hauteur des murs, la surface des ouvertures est réduite au minimum selon les directives sismiques et le toit est relativement léger. De plus, une structure en bois relie les fondations aux murs et au toit. La conception architecturale permet une ventilation traversante comportant une petite entrée et une grande sortie (Fathy Hassan, 1978) selon la direction du vent dominant en été. Le mur de la façade sud comporte une surface vitrée importante (38,64 %) ainsi qu'un débord de toit de 600 mm pour protéger les pièces du soleil d'été. La demande d'énergie de chauffage qui représente 91,1 % de la consommation d'énergie des logements de la ville de Kaboul a été analysée. Le bois et le charbon sont traditionnellement utilisés et sont considérés comme la principale source de chauffage du bâtiment. Le coût par mètre carré du bâtiment et des toilettes est égal à 56,6 \$/m².

ABSTRACT

Afghanistan has suffered from decades of war, causing massive migration from rural areas to the cities for better security and job opportunities; thus, the population increased dramatically, resulting in socioeconomic difficulties for Afghans. This influx of people to Kabul led to a massive development of informal settlements, which is problematic. Between 2002 and 2012 many modern townships were built. Informal settlements together with the townships have dramatically changed the Kabul landscape. On account of this, this thesis proposes that earth architecture should play a role in the rapid urbanisation of Kabul. *Accordingly, the aim of this research is to develop an applicable model for affordable housing construction in Kabul by using modern earth construction techniques.* For this, three sites including Deh-Sabz, Arghandi, and Band-e-Ghazi, were selected. Their soil physical characteristics have been determined in this thesis. In all the soils, the diffractograms mainly present calcite and quartz; to highlight the clay part, the samples are mainly composed of limestone and quartz. The wet sieve analysis showed that the clay and silt contents are high for Deh-Sabz and Arghandi soils, 98.0 % and 93.7 %, respectively. For Band-e-Ghazi soil, this percentage is only 31.2 %. A design mix was prepared for each soil type, and various earthen elements including sun-dried brick, compressed earth block (CEB), and compressed stabilised earth block (CSEB) were produced from each soil. The cement content represents 9 % of the dry granular mixture for Band-e-Ghazi soil and 10 % for other two soils. Whatever the earth element considered, the elements made with Deh-Sabz soil developed a better compressive strength than those with the two other soils. It was found that stabilisation of earth with Portland cement is not efficient because it consumes a large amount of cement and provides weak compressive strength. The dry compressive strength of CEB is higher than that of sun-dried brick. This means that the most suitable technique for producing mud brick in Kabul is CEB. A comprehensive evaluation index method was applied to optimise the structural layer of the CEB and develop a quantitative design strategy for the wall thicknesses suitable for the Kabul climate. The analysis found the optimum wall thickness to be 505 mm for the CEB wall. Considering this thickness, the heating demand which counts for 91,1 % energy usage in Kabul was also analysed.

Keywords: informal settlements, affordable housing, earth construction, block

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GENERAL INTRODUCTION

Suffering from decades of war, Afghanistan has witnessed massive migration of the rural population to the cities, seeking improved security, employment, and education for their children. Kabul the capital was designed for 1.5 million people; currently, it has approximately 5 million inhabitants (Hakim-Ebrahimi et al., 2022). In Kabul, rapid geographical changes occurred in 1979 when Russia attacked Afghanistan, and in 2001 when the USA and coalition forces arrived; many Afghans left their homes in war zones and moved to Kabul. Therefore, the population increased rapidly from 600,000 in 1970 to 1,500,000 in 1980 and to 4,860,880 in 2019 (Kazimee, 1977; Najimi, 2016; CSO, 2019). For a developing country, it is challenging to provide housing for this amount of displaced Afghans. The Ministry of Urban Development and Land (2019) stated that 70 % of urban populations live in these over-populated and densely packed settlements, while UNFPA (2015) place the figure at 72 %. This has resulted in a low quality of life, severe socioeconomic gaps amongst Afghans, and most importantly a lack of access to housing for many.

This influx of people and the inability of the government to provide housing instigated large developments of informal settlements. In 2004, 80 % of the Kabul population were living in these deprived areas, accounting for 69 % of the total residential area and providing shelter for 2,440,000 people (World Bank, 2006). The World Bank (2006) further claims that 12 % of this population live on hillsides and mountains, based on Ikonos satellite images. The Afghanistan housing policy stipulated 41,704 houses were to be built annually to address the shortage. However, the government and private sector reached a mere 5 to 10 % of this each year (MUDL, 2019). To address the housing demand for Kabul, it was estimated that an actual 17,163 dwellings per year between 2015 and 2019 were to be constructed, and 18,090 dwellings per year are projected for the years from 2020 to 2050 (UNFPA, 2015). The increase in the urban population will not stop, and by 2060, 50 % of Afghans are envisaged to be living in cities (UNFPA, 2015), leading to an increasingly severe housing shortage. Governmental inability, corruption, and the minimal availability of finances were the main problems hindering the provision of shelter to these citizens. The majority in informal settlements lack access to basic infrastructure, including water, drainage, sanitation, and waste collection. In Kabul between 2002 and 2012, 85 townships were built (Abdulraqib and Asano, 2014). Townships are medium raised apartment blocks gated communities. Informal settlements together with these townships have dramatically changed the Kabul landscape.

In Kabul, houses are traditionally built with sun-dried brick and pakhsa (cob). However, those townships and most of the informal settlements are built with modern materials, such as fired bricks, reinforced concrete structures, and glass facades. They are not insulated or connected to central heating, thus consuming more energy than is affordable for low-income Afghans. Moreover, modern courtyard housing in Kabul is deteriorating vital social rites, exchanges, patterns of living, whereas traditional Afghan housing supports these social and cultural values. Contradicting many developing countries with uncertain and fragmented experience of social life, Afghan's traditional housing is directly connected to Afghan culture (Watts, 1983). Therefore, traditional earth architecture should play a role in the rapid urbanisation of the Kabul. This building method has been used for centuries in Kabul, adaptive to the local environment and culture; people know how to build with it etc.

To provide shelter for these low-income populations in Kabul, there is a need for mass construction of low-cost housing. To reduce the total cost of this housing, local materials can be and have been used for years, significantly reducing manufacturing and transportation costs, accounting for 35 % of the total costs (Yu and Hao, 2022). Building with earth traditionally has been used for centuries in Kabul, hence the existing knowledge there. Fortunately, Kabul is rich in local materials, such as raw soil and stone; however, the use of the soil suffers from a lack of use of modern construction technique. People use traditional techniques that require increased effort, time, and which have produce minimal mechanical strength and durability. Therefore, the use of traditional earth construction techniques seems not an adequate solution for the mass construction of affordable housing in Kabul.

This research provides a base for the construction of affordable housing in Kabul. The use of local materials and the application of modern methods and technology can help this mass construction of residential housing. The experience and available technologies in developed countries encourages the use of modern earth construction methods. Kabul soil has been analysed in this thesis to develop earthen elements and mortar. Standard model houses have been designed and thermally analysed. The optimum wall thickness and minimum energy demands of the model houses have also been evaluated. The research is presented in the following six chapters:

Chapter 1 explains the context of the study, including the aim and objectives, geophysics, climate, seismic, and architectural aspects of housing in Kabul, Afghanistan.

Chapter 2 focuses on the state of art, and it examines the earth architecture and earthen construction techniques used in Afghanistan in the past. It further analyses modern earth construction, its social value and energy demands. The common vernacular housing form, roof shape design, and ventilation systems in Afghanistan are also investigated here. Further the methodology explained in this chapter.

Chapter 3 examines the physical properties of the three types of soil from Kabul: the location, XRD analysis, texture, hydraulic properties, suitability for construction, standard Proctor tests conducted, and their linear shrinkage limits.

Chapter 4 investigates the three earthen elements (sun-dried brick, compressed earth block (CEB), and compressed stabilised earth block (CSEB)) produced. Their mechanical strengths, durability, thermal properties, and binder intensity index are also analysed. This made it possible to select the best element for construction for the affordable housing programme in Kabul. Necessary analyses were also performed to find the optimum design mix for the earthen mortar. Finally, sample structure walls from the selected earth element and mortar were built and tested under different mechanical strengths.

Chapter 5 focuses on the optimisation of the wall thickness for the model and analyses the energy demand. Finally, a complete model for affordable housing in Kabul is proposed.

Chapter 6 explores existing models of low-cost housing by UN-Habitat and the Ministry of Urban Development and Land, and the design morphology and building layout of existing housing in Kabul is explained. Three-prototype models for this affordable housing programme are proposed, and a design concept justifying the design of those models has been developed. Out of the three, one model was selected for the final analysis.

CHAPTER 1
CONTEXT OF THE STUDY

CHAPTER 1: CONTEXT OF THE STUDY

1.1 Aim and objectives

These recent decades of war and instability in Afghanistan made it compulsory for many Afghan citizens to move to the cities where they could find relatively enhanced security. Kabul has thus experienced a rapid population growth over the last few decades and centuries (see Tab. 1).

No	Period	Population
1	1700	10,000
2	1876	140,000
3	1929-1936	120,000
4	1951	250,000
5	1970	600,000
6	1980	1,500,000
7	2019	4,860,880

Table 1: Kabul population growth (1700-2019) (CSO, 2019; Kazimee, 1977; Najimi, 2016)

These displaced people require housing. Article 14 of the Afghanistan Constitution states that “the state shall adopt necessary measures for the provision of housing and distribution of public estates to deserving citizens in accordance with the provisions of law and within financial possibilities” (Constitution, 2004). With this growth in urban populations, it is clear to see the urgency for affordable housing in large cities, such as Kabul. The principle barrier to this provision is the government, as ascertained in the General Introduction (see page 1), leaving many Afghans to live in below-standard informal settlements that are detrimental to health and safety due to their lack of basic sanitation and infrastructure. To exemplify how life is in these informal settlements, residents buy water brought by donkeys on a daily basis. Figure 1 shows an aerial image of one of these informal settlements, at the top of Kabul’s TV Mountains, demonstrating the high density; when this is considered along with the sanitation and infrastructure issues, it further highlights how necessary it is address this situation and provide its residents with adequate housing. Recently, many small- and medium-sized concrete residential townships were built in Kabul; however, they are expensive and unaffordable for low-income Afghans (see Fig. 2). Between 2002 and 2012 in Kabul, 85 township were developed (Abdulraqib and Asano, 2014).



Figure 1: Informal settlements on the top of Kabul's TV Mountain (Archival Store, 2020)



Figure 2: From left to right: newly built township of Aria city and Shahrak Telayee (photograph by the author)

The modern urbanisation occurring in Kabul means that there is a loss of social and cultural aspects of life where residents must live differently to what they are accustomed to. It deprives its residents of opportunities for social interaction due to the way that the houses are designed. However, in traditional Afghan courtyard housing designs, the cultural and social values are maintained. In the old city of Kabul, flat roofs were surrounded by 1.5 to 1.7 m high parapet walls where neighbouring residents spend their free time with others. They are built with and by local materials, labour, and traditional techniques. Therefore, traditional architecture reserves an importance in the rapid urbanisation of Kabul. What is required is a strategic, incremental, and planned growth of the city. These traditionally designed houses require modern techniques and methods to reduce costs. More specifically, architecture in traditional societies is a direct translation of its people in terms of their social, cultural, and physical needs (Watts, 1981), and it is that requires preserving.

Urban populations increase daily worldwide. In Afghanistan, it has been reported that by 2060, 50 % of Afghans will be living in cities (UNFPA, 2015). Currently, the World Bank, Asian Development Bank, UN-habitat, and countries including United Arab Emirate and China are providing aid for the construction of housing in Kabul. To benefit from such an opportunity and maximise the use of local resources and modern technology to provide cheap housing, this thesis aims to address the best types of affordable housing with the appropriate materials required. With the limited financial resources and political uncertainties, this research aims more specifically to develop an applicable and practical model for affordable housing construction in Kabul. The use of local materials and modern technology are considered essential for the mass construction of residential housing. Unfortunately, in Kabul, the use of raw soil suffers from a lack of modernisation in terms of how it is used and applied in building. Local people use the traditional techniques in the informal settlements, which is more time consuming and which produce houses with less strength and durability. The experience and available modern earth construction technologies in developed countries will be the basis for this research. A further aim is to encourage the use of modern earth construction methods in Kabul and to develop a standard code of practice for the production and use of earthen elements. Such elements are already being produced by the industry and on construction sites and thus are available for use for the mass construction of affordable housing in small and big cities.

On 15 August 2021, the political change and takeover of Afghanistan by the Taliban placed uncertainty in terms of the viability and application of this project in Kabul. However, there are hopes that Taliban's unrecognised government will not last for long, primarily since they are a small group and do not represent all the ethnicities in Afghanistan; secondly, they have proven to be not able to professionally and administratively run the country. Therefore, this research benefits from the laws, regulations, and constitution that were made during the twenty years of the republican government in Afghanistan.

1.2 Geophysical aspects

1.2.1 Kabul location

Afghanistan is located in the centre of Asia, south of Tajikistan, Turkmenistan, and Uzbekistan, northwest of Pakistan, southeast of China, and east of Iran (see Fig. 3). Three-quarters of the country is mountainous. These mountains divide the country into three main regions, the central high lands, northern deserts, and the south-western plateaux (Samizay, 1974). There is no oceanic border to the country. Kabul has been the capital of Afghanistan since 1775, and it is the centre of administrative, political, business, and trade activities. It is located in the eastern section of the country and has 22 districts (see Fig. 4). Kabul sits at 1,791 m above sea level, geographically located between the latitude of 34°32' N and longitude 69°12' E (Wafa et al., 2020). This elevation makes it the highest capital in the world. The Kabul valley is surrounded by high mountains at a crossroads of northern, southern, eastern, and western trade routes. The major routes surrounding the city connect Kabul to other large cities, such as Mazar-e-sharif, Khost, Jalalabad, Kandahar, and Herat. Kabul also borders six provinces: Parwarn, Kapisa, Logar, Jalalabad, Wardak, and Laghman.



Figure 3 : Afghanistan political map (University of Texas Library, 2020a)

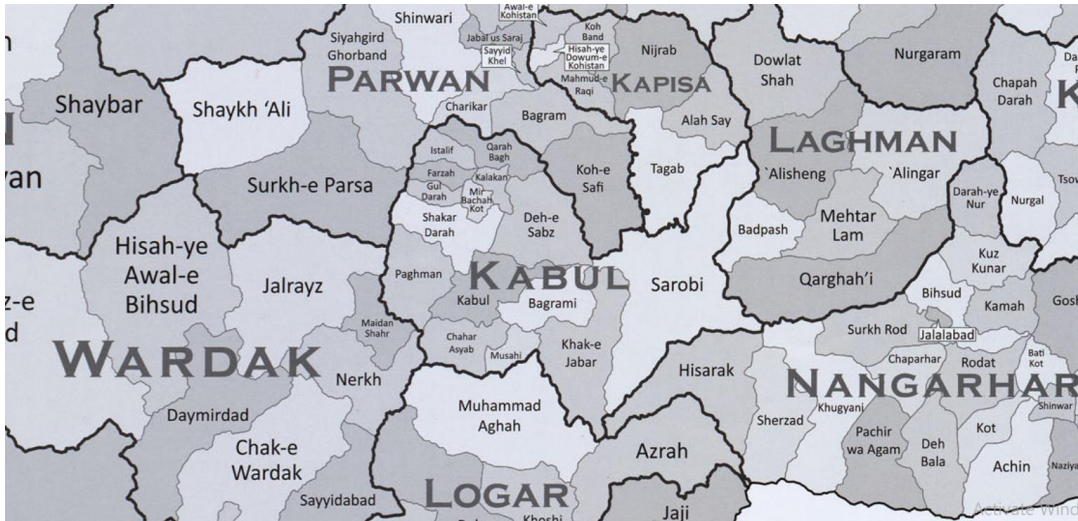


Figure 4: Kabul location and districts (University of Texas Library, 2020b)

1.2.2 Geology

The topography of the country is dominated by the Hindu Kush Mountains, entering Afghanistan from Kashmir, Pakistan in the northeast and from the southwest and west of Iran. Hindu Kush meets the Pamir Mountains in the centre of the country. Geologically, they are recently originated mountains that are still growing; they represent key features in the geography of Afghanistan (Szabo and Barfield, 1991). Their height and form determine the wind and precipitation patterns, river flow, and vegetation; further, they are the main origins of the severe seismic activity in the country (Szabo and Barfield, 1991). The high mountain ranges make a unique geography for the country (see Fig. 5). Afghanistan is an agricultural land, and the location of the rivers accounts for the definition of the land and the distribution of population settlements along them. Before the 1960s when the roads did not connect the regions, it was difficult to transport agriculture and fertiliser from the north to the mountainous and arid south (Szabo and Barfield, 1991). In short, every region has its own unique landscape and features, and with its own local materials. This is relevant to this project since soil type and local materials are essential to sustain the proposed housing programme.

Kabul with a size 1,049 km² is geographically dominated by mountains and deserts, which accounts for 56.7 % of all domains, and the plateaux account for 37.7 % (Wafa et al., 2020; UNFPA, 2015). Kabul has a 700 km long river, originating in the Hindu Kush Mountain in the Wardak province to the southwest of Kabul, which provides water to the city. A geological map of Kabul and nearby regions is shown in Figure 6.



Figure 5: Afghanistan map of its mountains and elevations (University of Texas Library, 2020a)

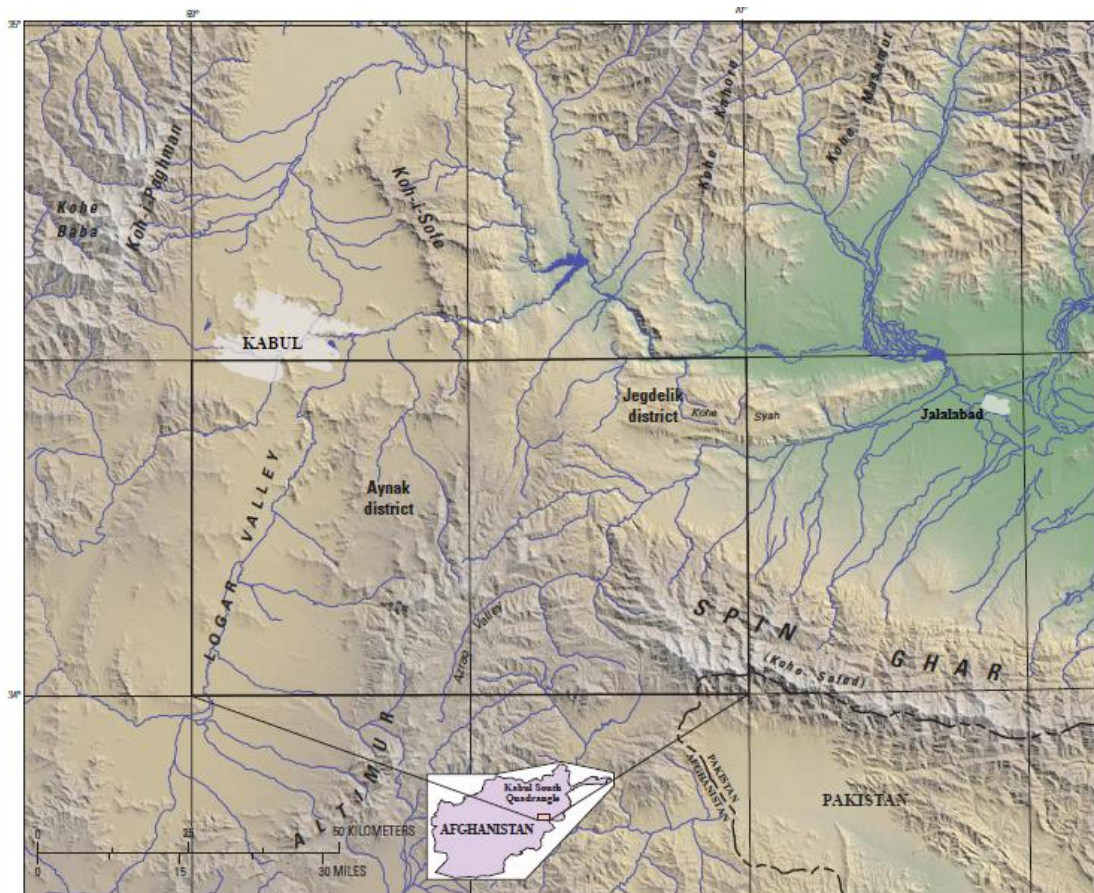


Figure 6: Kabul south-quadrangle map (Bohannon, 2010)

The rocks and minerals in Kabul present an interesting combination of minerals, from distinct periods, and a variation of rocks and sedimentations (see Fig. 7). Nonetheless, certain of these existing minerals are understudied. This thesis has selected three areas for which to study the soil and earth content in view to designing this affordable housing programme for Afghans in the townships, informal settlements, or for those without any housing at all. The three areas are marked in red and have the following mineralogy:

- Deh-Sabz district (Q3a and Q3loe minerals) has its origins in the *Late Pleistocene Period*, and it contains loess, conglomerates, and sandstone, and shingly and detrital sediments. Gravel and sand are more abundant on the north side of the area, close to the mountains.
- Arghandi, south of Paghman district (K1gbm and Q3loe minerals), stems from the *Early Cretaceous and Late Pleistocene Periods*; it contains Gabbaro and monzonite, and it is more abundant in diorite than granodiorite. Moreover, Loess is more abundant than sand and clay,
- Band-e-Ghazi, south of Sorobi district, (N2cgs and P2um minerals), originates in the *Pliocene and Paleocene Periods*; it contains conglomerate and sandstone, which are more abundant than siltstone, clay, limestone, marl, gypsum, salt, felsic, mafic, shale, and volcanic rock.

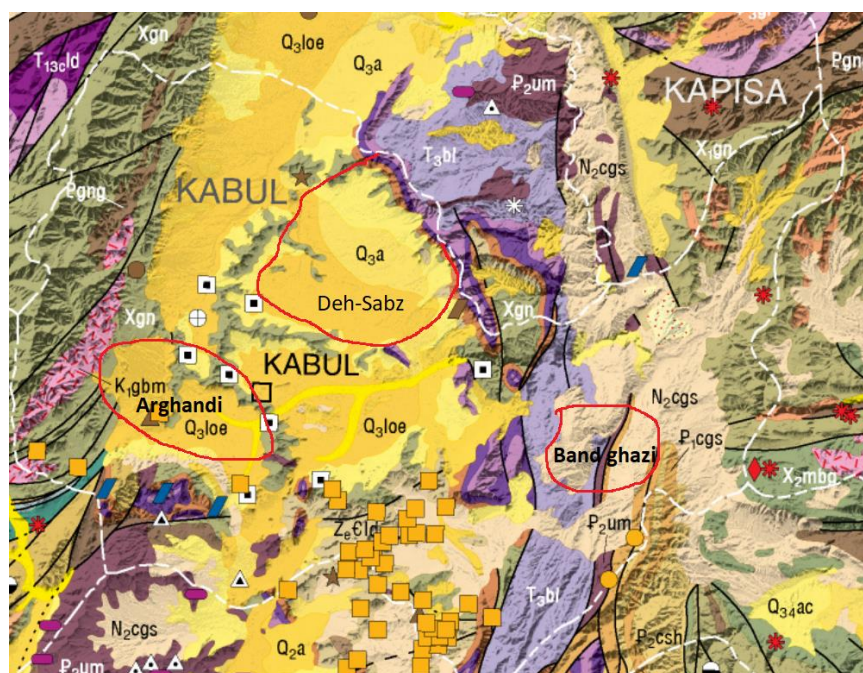


Figure 7: Map of the geology and mineralogy in Kabul (University of Texas Library, 2020c)

1.2.3 Climate

Afghanistan has a semi-arid continental climate with potential variations in temperature and precipitation in the different seasons. As with a desert, the climate is hot in summer and cold in winter. The lack of a border with any ocean results in less humidity and less cloud and rainfall in the country. Therefore, the weather in different parts of the country depends on the mass of air which comes to the country. These masses include Siberian polar cold air mass, Iceland island oceanic mass, Indian Ocean air mass, and Persian Gulf wet hot air mass (Civil Aviation Authority, 2020). Moreover, the temperature varies according to the altitude; the mountainous north-eastern region annually experiences temperatures below zero, while the lowly elevated southern parts have temperatures over 35 °C. Precipitation is affected by the topography since the southern arid land has less than 150 mm rainfall on an annual basis, while the northeast mountainous region has more than 1,000 mm (World Bank, 2020). Generally, any precipitation rate of less than 150 mm annually is considered dry, and above this range is seen as a wet climate. Afghanistan's average monthly temperatures and precipitation are shown in Figure 8.

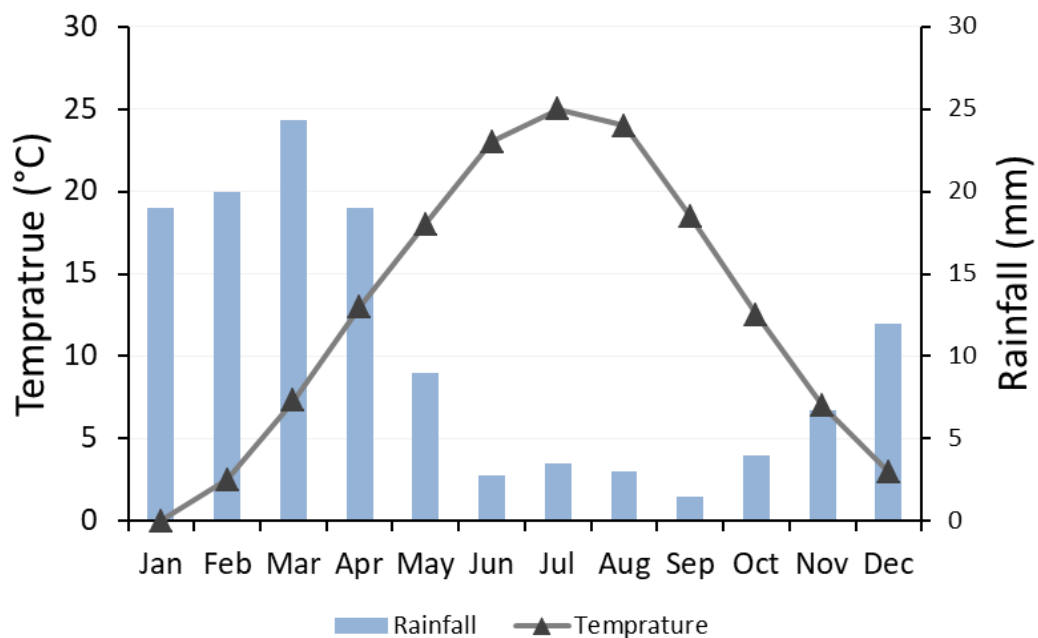


Figure 8: Afghanistan's average monthly temperature and precipitation (1901-2016) (World Bank, 2020)

Kabul weather is affected by Siberian polar cold air masses, so it has a snow in winter and a rainy spring. According to the Köppen climate classification, Kabul has a cold desert climate, with dry, cold winters but also dry, warm summers (Wikimedia commas, 2022). In winter, temperatures decrease to $-8\text{ }^{\circ}\text{C}$ while in summer, they increase to a maximum of $38\text{ }^{\circ}\text{C}$. The averages of the temperature and precipitation analysis for Kabul are shown in Figure 9. The maximum temperature of an average day for each month for Kabul is represented by the solid red line. The solid blue line shows the average minimum temperature of an average day for each month. The dashed red and blue lines show the average hottest days and coldest nights for each month, respectively.

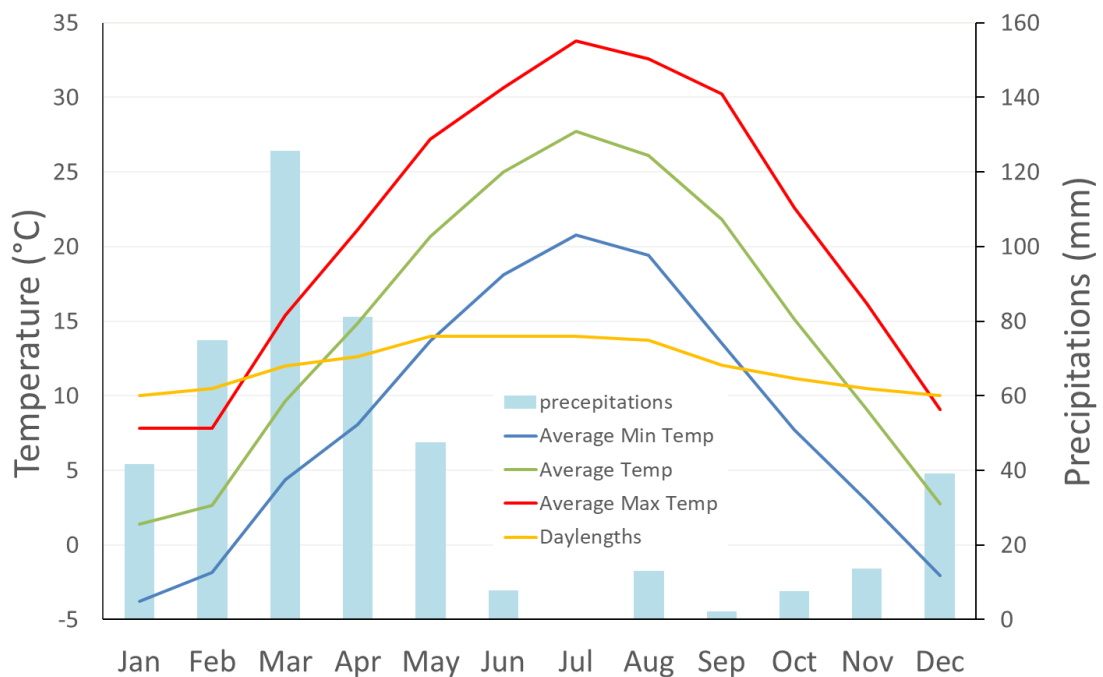


Figure 9: Kabul's average temperatures and precipitation

Depending on the seasons, the annual relative humidity for Kabul is between 20 and 61 % (see Fig. 10).

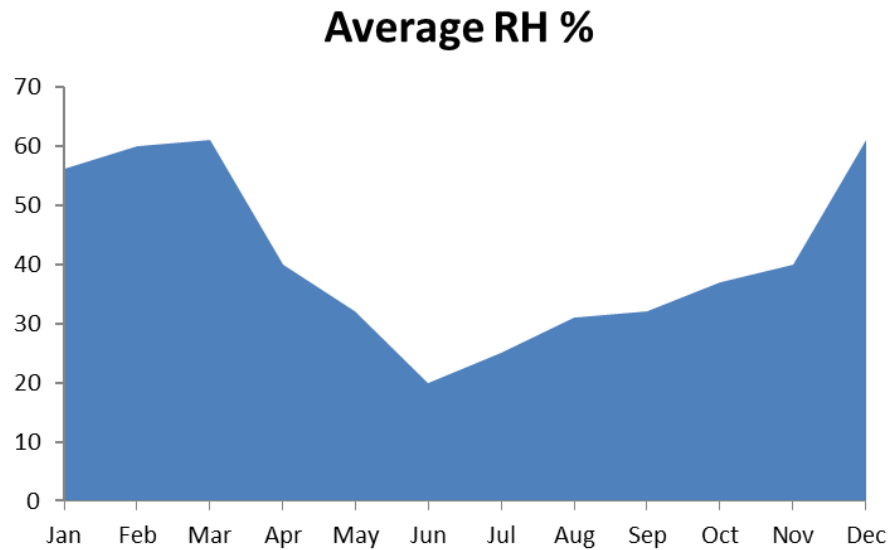


Figure 10: Kabul's average relative humidity

The energy analysis for Kabul is summarised in the psychrometric chart in Figure 11. For Kabul's housing comfort zone, a dry bulb temperature between 19 and 26 °C is generally accepted by professional. Based on the comfort zone, the analysis shows that there is an increased energy demand for heating compared to cooling in buildings. With a passive design, including appropriate orientation, bioclimatic approach, cross ventilation, and a well-designed building envelope, the energy demand can reduce dramatically and building become desirable in view of the Kabul climate.

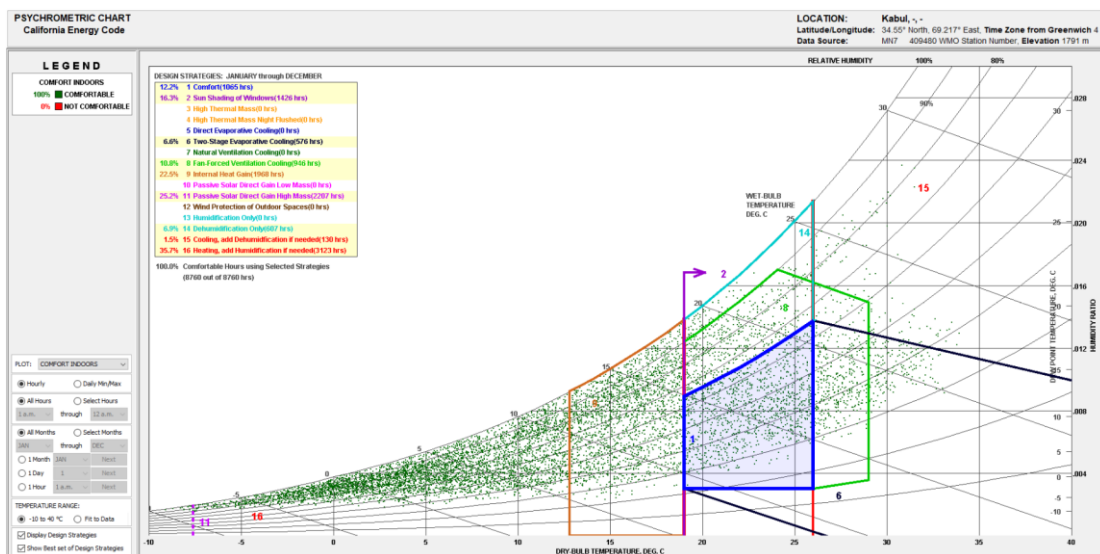


Figure 11: Psychrometric chart for Kabul (Climate Consultant Software)

The climatic seasons method developed by (Garcia, 2018) is based on the definition of six seasons (see Fig. 12). Maintaining the same comfort zone used in the psychometric chart and considering a tolerance of 5 %, the Kabul climate is characterised by six months of Season 1, two months of Season 2, two months of Season 4, and two months of Season 5. The raw data from the Kabul weather station have been downloaded using degree-days weather data developed by the BizEE software (degree-days, 2022). The analysis shows that the thermal stress is around 2,840 °C degree-days per year, mainly for Season 1 (41.7 %) and Season 2 (25 %). Heating accounts for 91.9 % of the energy demand, compared to 8.1 % for cooling. The finding was compared with the weather data of Montpellier city in France. By contrast in thermal stress, the climate in Montpellier is also characterised by six months of Season 1, two months of Season 2, two months of Season 4, and 2 months of Season 5, with a thermal stress around 1,861°C degree-days per year.

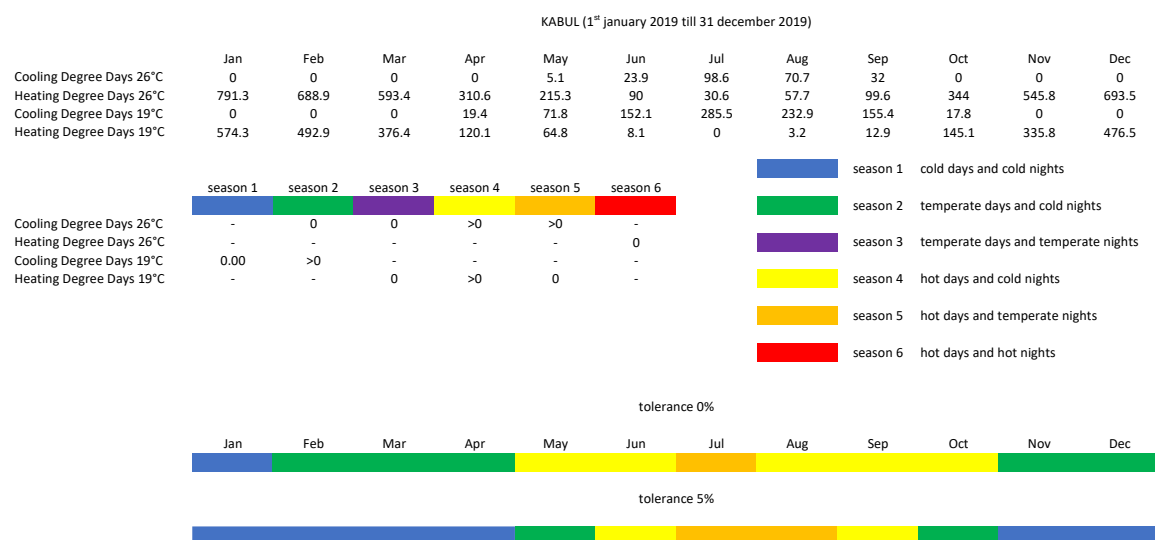


Figure 12: Climate seasons method and its application for Kabul (GARCIA, 2018)

1.3 Seismic aspects

1.3.1 Seismic risks

In Afghanistan, seismic data and documentation are scarce. The minimally available research indicates that most parts of the country are seismically inactive; however, the most densely populated northern and eastern regions are active and have experienced significant seismic activity, especially the northeast of Afghanistan and north of Kabul (Ambraseys and Bilham, 2003). Moreover, scholars Quittmeyer and Jacob (1979) and Lawrence et al. (1992) agree that in Afghanistan, four seismically active faults exist: Chaman, Darwaz, Harirud, and Central Badakhshan. Nonetheless, Leven (1997)

described in the United State Geological Survey that Bohannon (2010) had also prepared a faults map for the country, illustrating that there are major faults shown with thick lines and minor faults with thin lines (see Fig. 13). In contrast, Leven (1997) found the following faults: A: Har-i-Rud, Panjshir, and Wakhan (HPW); B: Chaman-Paghman; C: Gahzni; D: Tagab; E: Kunar; and F: Sorubi. Moreover, seismic severity in various parts of Afghanistan is not the same since the country is divided into various earthquake zones (see Fig. 14): A, B, C, and D (Guideline, 2003). In Afghanistan, the guidelines for earthquake resistant construction apply these zone divisions. This enables architects to design buildings based on the intensity of seismic activity in different zones. The seismic zone factor for Kabul is considered to be 0.16 (Guideline, 2003). Kabul is geographically located in Zone C with moderate earthquake damage risk, as previously mentioned.

Kabul is geographically located between many faults: to the west is fault B; to the northeast D; and to the east F. However, fault B to the west of Kabul in Paghman district is seismically active and has witnessed some severe earthquakes over the years. In Kabul, there were recorded earthquakes in the year 1505 (with a magnitude (M) of 7.3) and in 1874 (M 7) (Boyd et al., 2007). However, there is no documented report about the casualties of these earthquakes. The magnitude characterises the size of an earthquake, measured based on the maximum motion recorded by a seismograph.

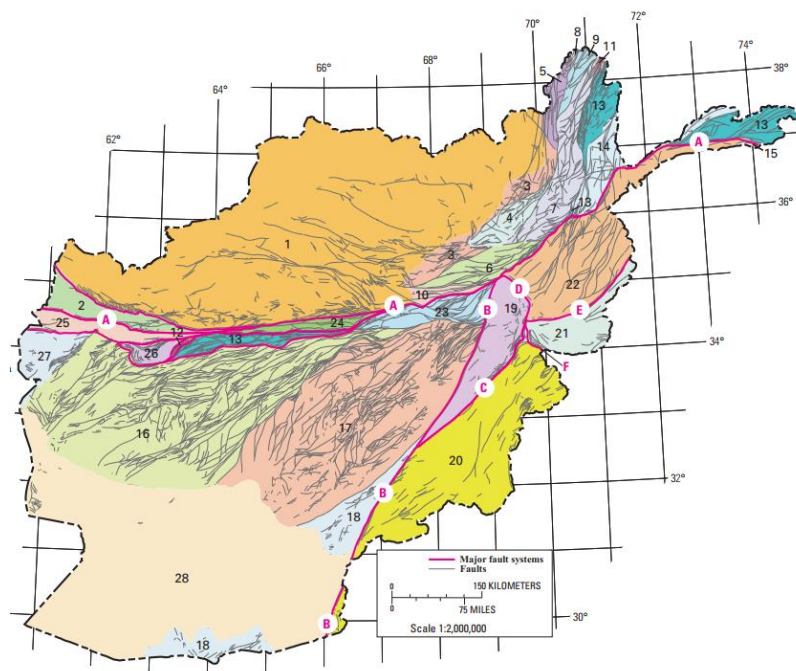


Figure 13: Afghanistan map with the major and minor faults (USGS, 2010)

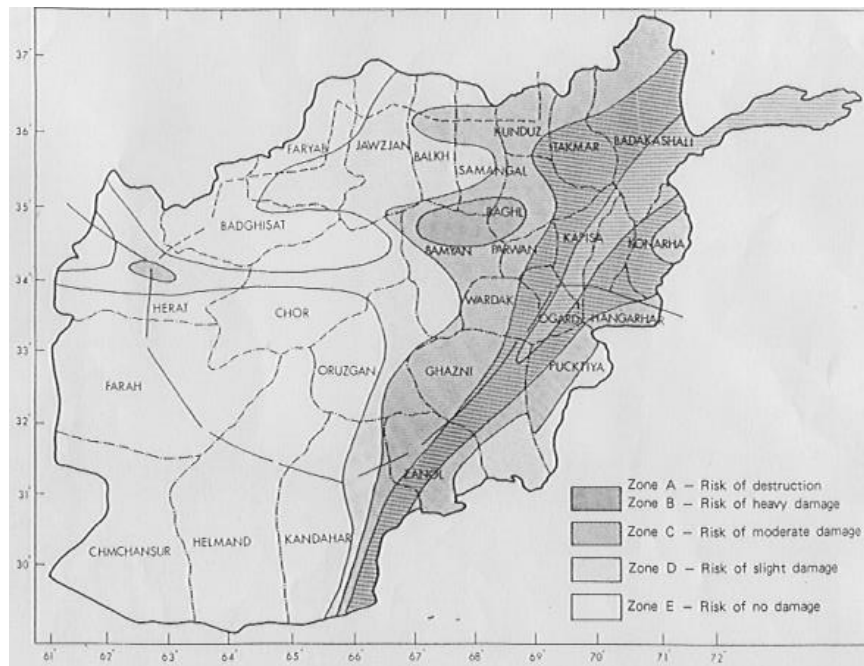


Figure 14: Afghanistan seismic zones (Guideline, 2003)

1.3.2 Consequences on architectural forms

Building with earth is low cost and readily available, however, precautions must be taken to improve its ability against flood, humidity, and earthquakes. Moreover, when using earth, it is essential to consider its real-world applications and not to stretch it past its actual capacity. Sun-dried brick houses are unable to withstand seismic activity and are likely to collapse under the pressure of heavy ground shakes. The low-seismic resistance of earthen buildings is linked to the high density of the bricks, their low mechanical strength, in particular under tension, and their low flexibility (Blondet et al., 2011). Earth buildings are extremely capability against gravity loads, but their resistance against lateral forces is weak.

A report by USAID (2007) showed that in Afghanistan over the last 4,000 years, many devastating earthquakes have occurred; in the last ten years, 7,000 people have died as a result. In 2002, an earthquake (M 6.1) in Baghlan, Nahrin district killed 1,200 people and destroyed around 2,000 dwellings (see Fig. 15; Yeats and Madden, 2003). A recent devastating earthquake in eastern Afghanistan in June 2022 produced an after shake in July 2022. According to the news by BBC (2022), at least 1,000 people died, and more than 3,000 were injured in Paktika. Hundreds of earth-made houses built on the mountain side were destroyed (see Fig. 16). In 2005, in Kashmir, Pakistan with many houses built with sun-dried bricks, an earthquake (M 7.5) demolished the villages and the dwellings within it. According to USAID (cited in Boyd et al., 2007), more than

69,000 people died and 85,000 were injured. This shows the vulnerability of mud-brick houses against natural disasters.



Figure 15: Typical damage in Nahrin district, walls collapsed completely, (Yeats and Madden, 2003)



Figure 16: Earthquake damage to earthen houses in Paktika, Afghanistan (BBC, 2022)

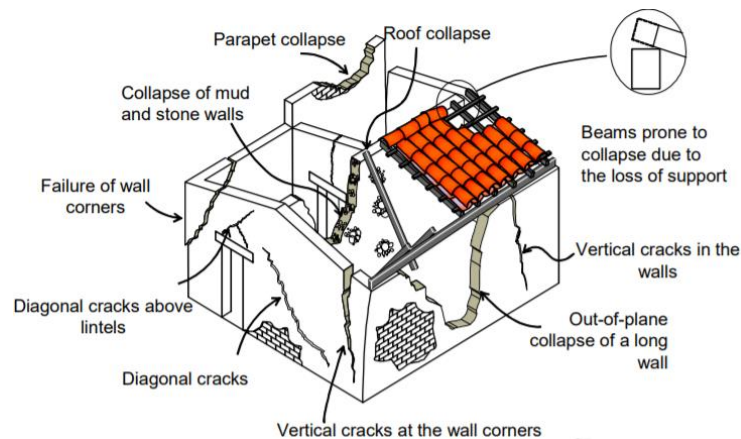


Figure 17: Potential damage to buildings (Blondet et al., 2011)

The typical damages to sun-dried brick houses are summarised in Figure 17 by Blondet et al. (2011). The building layout and form affect their stability against the force of an earthquake. It has been shown that symmetric plans and elevations demonstrate an enhanced resistance, addition of small structures with one room or staircase connected to a larger room to make the structure dissymmetric and vulnerable to an earthquake (Houben and Guillard, 2014). Simple rectangular shapes are seismically more

appropriate compared to complex forms. One-story buildings are seismically more earthquake resistant than two story ones (Guideline, 2003; Minke, 2012). Moreover, a combination of frequent cross walls (cellular) similar to a box (Blondet et al., 2011; Minke, 2012) seismically improve building stability (see Fig. 18). Blondet et al. (2011) have emphasised the following essential features when constructing mud-brick houses that is to pertain to: one story; a lightweight insulated roof; a firm foundation; certain wall thicknesses, lengths, and heights; length of openings 1.2 m max, and proportional with wall lengths to promote stability against seismic shakes (see Fig. 19).

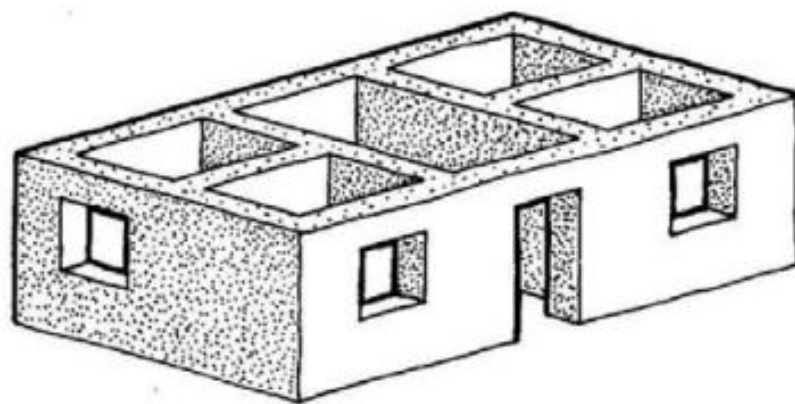


Figure 18: Compact plan with cross walls and proportional windows (Blondet et al., 2011)

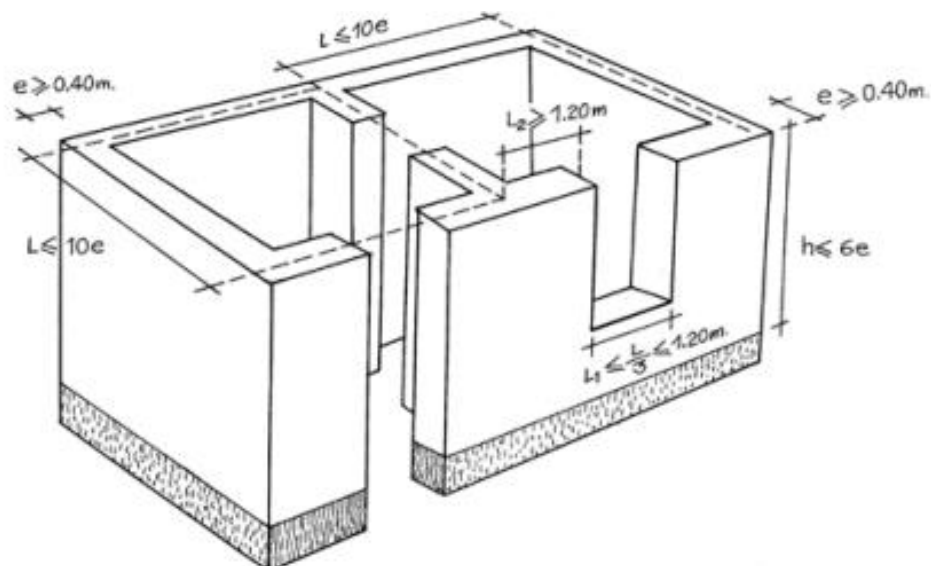


Figure 19: Metric measurements and wall sizes (Blondet et al., 2011)

1.3.3 Devices for seismic resistance

Site location, topography, soil type, foundation width, roof weight, wall joints, and humidity are all important to consider while building with earth (Blondet et al. 2011). Soil should have a certain rigidity to be an effective foundation and structure. It is advisable to build a uniform foundation on the same level and avoid foundations on different levels; there is a direct relation between soil type, foundation thickness, and the height of buildings (Houben and Guillard, 2014). When height increases and the soil is soft, the foundation thickness also increases. Lightweight insulated roofs joined with rings are seismically better in comparison to heavy roofs. Walls having a firm connection together, vertically and horizontally, especially in the joints, improve building rigidity against shocks and potential collapse. Regular maintenance and protection from humidity further enhances building longevity and resistance against seismic activity. Houben and Guillard (2014) believe that soil with a minimum bearing capacity (0.1 MPa) could be used to construct a building on, and that any less should be avoided. Moreover, in terms of building a one-story house, a minimum foundation width (0.6-0.7) m on firm and soft soil should be considered (Guideline, 2003). The shape and type of bricks, flat to the earth and overlapping at vertical joints affect the wall-bearing capacity. Flat bricks with less friction bonded with quality mortar improve wall integration. Well-finished flat interlocking bricks are seismically more sophisticated compared to solid sun-dried brick, even though there is problem with storage (Houben and Guillard, 2014).

A common practice is to reinforce walls vertically and horizontally with a variety of mostly locally available ductile materials. This reinforcement strongly improves the bending and tensile strengths of buildings. The materials include bamboo, cane, reed, vine, rope, timber, check wire, barbed wire, and steel bars (Blondet et al., 2011). For the horizontal reinforcements (Guideline, 2003), there is advice on two types of band: lintel bands have to be provided under the lintels for the doors and windows; ceiling bands have to be provided below the roofs and ceilings. Figure 20 shows a detail of ceiling lintels and their utilisation in a circular and sawn-wood wall corner. Minke (2012) claims that in seismic areas, walls need to be finished with a horizontal ring, connected with the hard foundation by columns. Heavy roofs made from slab, slate, and tile should be avoided, and the opening lintels must penetrate at least 40 cm into the wall. Further, for the high seismic zones (A and B), the guideline advice is on using a

combination of vertical and horizontal reinforcements for the entire wall (see Fig. 21). The reinforcements must be tied together and also with the lintels and the foundation. This reinforcement provides a stable matrix in contrast to the individual wall components. However, the guidelines do not illustrate the traditional methods of sun-dried brick construction reinforcements that exist in Kabul (Guideline, 2003). A typical traditional house in Murad Khani (the Peacock House) described in the Domestic Building Section of this study explains this reinforcement method in detail.

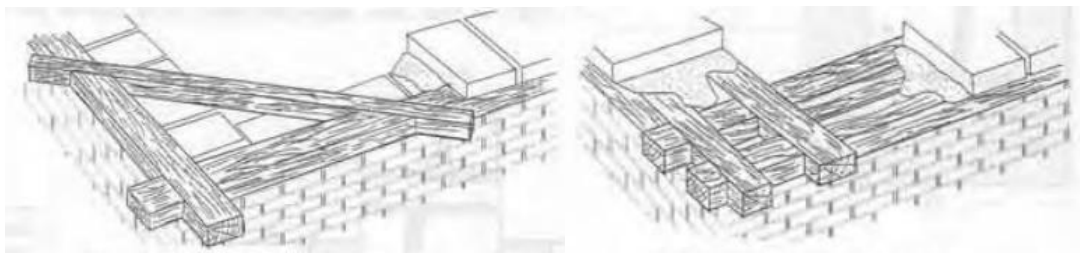


Figure 20: Horizontal ceiling band construction (Guideline, 2003)

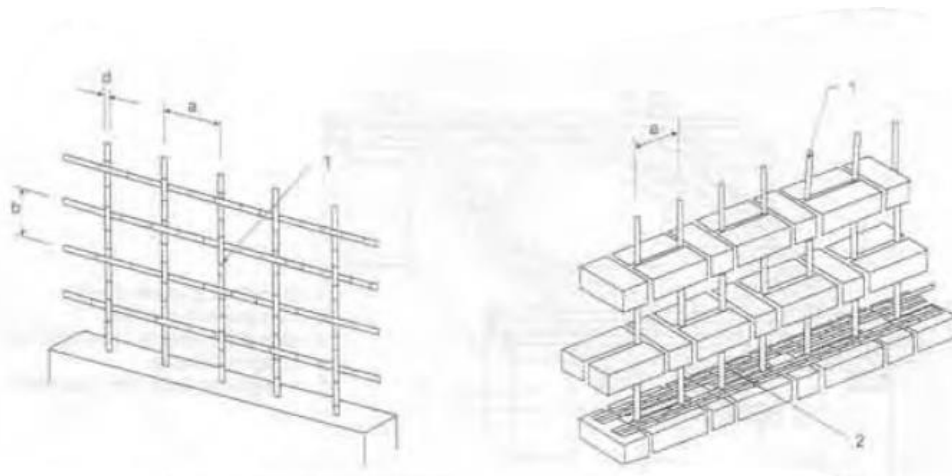


Figure 21: Combination of horizontal and vertical wall reinforcements (Guideline, 2003)

Using buttress and pilaster is another method, which can improve wall stability in the corners and T-junctions. Pilaster increases the stability of the structure in two ways: with forms of overlapping over walls to support overturning and to also integrate walls by working as a perpendicular column (see Fig. 22) on the back wall (Blondet et al., 2011).

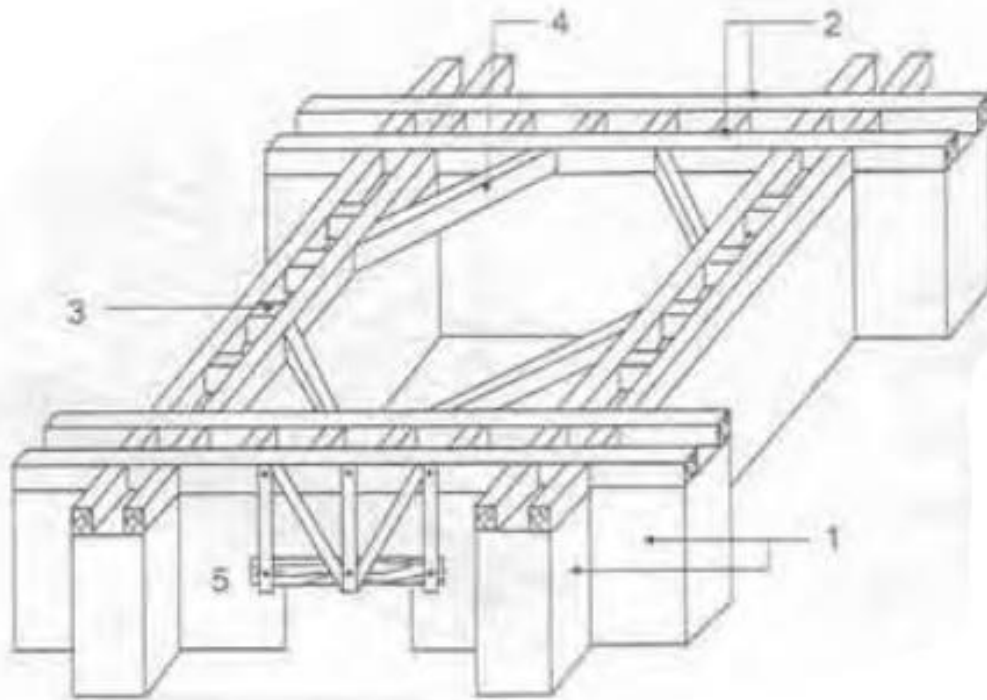


Figure 22: Timber extended to the buttress (1) wall (Guideline, 2003)

1.4 Architectural aspect

1.4.1 Domestic architecture

Afghanistan has been ruled by China and India, in terms of countries, and Buddhists and Islamists, in view of the dominating religions and philosophies; they have left their mark on the country's architecture (Najimi, 2004). Nonetheless, in these modern times, only the Islamic the latest architectural features and buildings remain visible. This is due to continuous war in the country which prevented preserving the ancient buildings. Afghanistan has a variety of distinct nomadic and sedentary styles of architecture, and there are almost twenty different ethnic groups with distinct traditional ways of living and cultural heritages (Szabo and Barfield, 1991). The rich and domestic architecture in the country is also due to its internal cultural diversity and neighbouring countries' influence. Every ethnicity uses a special form and tradition of making a shelter, ranging from tents, yurts, flat- and curved-rooved homes, single buildings, and typical village houses that maintain the balance between the physical and cultural needs of the people (Hallet and Samizay, 1980). The use of natural and local materials, such as clay, stone, and wood has produced a balance between people and their environment.

In contrast to developed and industrialised countries, which rely on modern materials, such as concrete, steel, and glass, local materials have created a rich form of architecture in Afghanistan that relies on the surrounding nature (Szabo and Barfield, 1991). Physical and cultural factors are important in creation of traditional architecture, where physical relates to the actual physical context or natural surroundings, as explained above in terms of using the local materials, while the second is concerned with religion and beliefs (Szabo and Barfield, 1991).

The usual construction materials for making buildings are sun-dried brick and cob, locally known as Pakhsa. In Kabul's old part of city, there exists the example of buildings made with Pakhsa, bricks, and a wooden structure for residential houses. However, for public buildings including mosques, shrines, and temples, durable materials, such as marble and fired bricks are used (Najimi, 2004). Interestingly, even with the development of modern earth construction methods, Afghans use the traditional techniques with limited modification. The strategic location of Afghanistan makes it a principal trading route to neighbouring countries, and this has affected their civilisation, housing forms, and ways of life. In the north, people use yurts as a form of shelter while in the south, tents are used more extensively; peasant communities use cluster dwellings, surrounded by walls and with towers for prestige and defensive purposes, where families of the same familial branch live close together as a community (Szabo and Barfield, 1991). Qala has separate places of worship (see Fig. 23); by contrast, the nomads and animal breeders use single dwellings for all, but which still exist in a cluster form (Najimi, 2016).

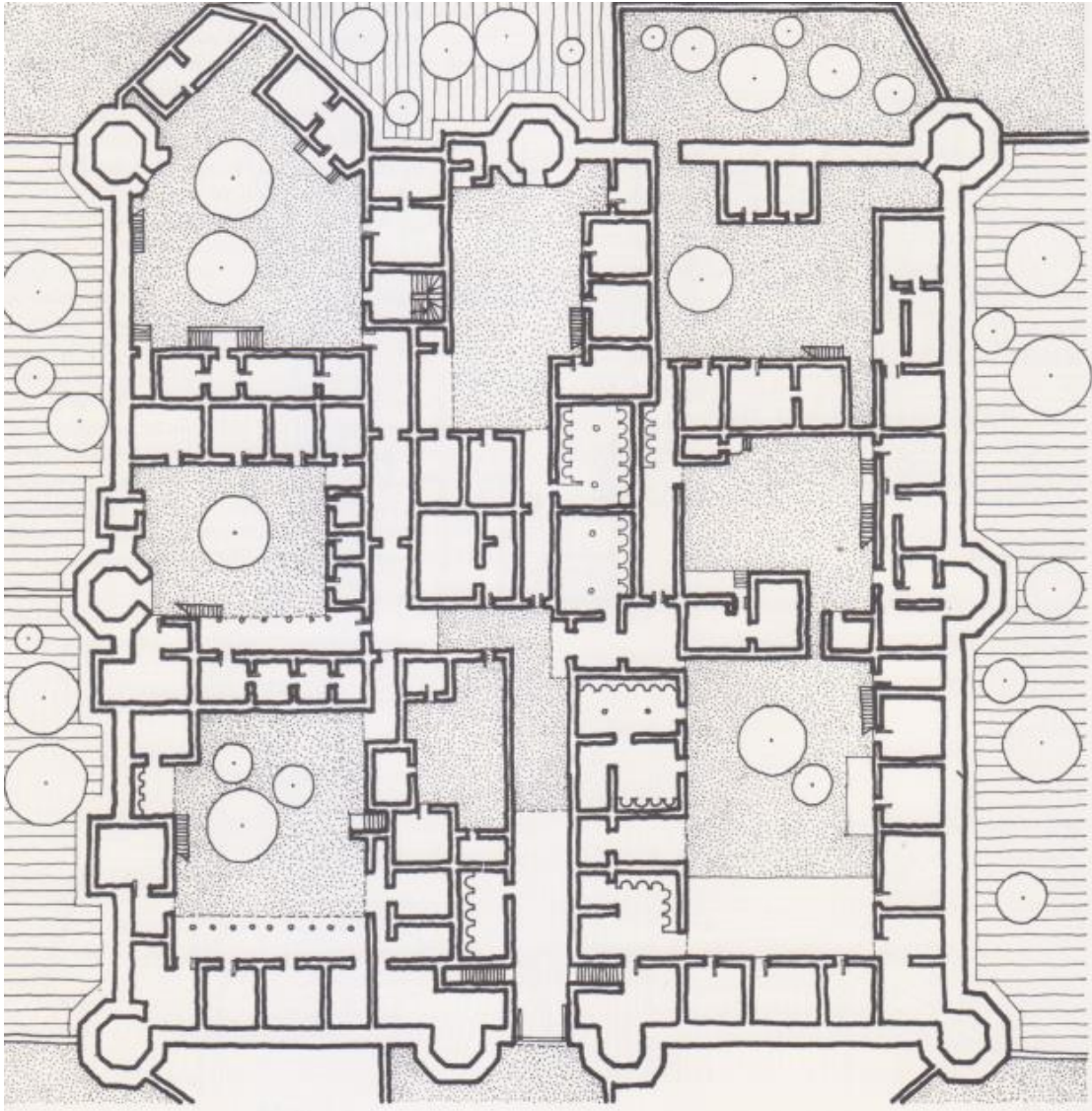


Figure 233: Plan of a Qala in Shiwaki-Kabul with nine families and a guesthouse (Samizay, 1980)

However, since Szabo and Barfield's (1991) research study, there has been relative changes to the Afghan way of life. Only the nomads who seasonally migrate from one place to another place use yurts and tents for their temporary stay. The farmers who work on agriculture prefer building single houses, rather than clusters of dwellings. In places such as Nuristan where wood is abundant, houses are made with wooden structures and fill in with stones and mud (Najimi, 2016). The roofing of the houses also varies; in the west and southwest of the country, including Herat, Farah, and Zarang, where there is a lack of wood, flat, dome, and vault roofs (see Fig. 24) are made with massive sun-dried bricks and Pakhsa walls (Szabo and Barfield, 1991). Curved roofs, mainly constructed of wood in Kandahar, but because of insects called *Wina*, the wood cannot last for a long time (Szabo and Barfield, 1991). However, flat

roofs are used in most part of the country, including Kabul. These roofs have multiple usages: creating an outdoor living space in the summer, and for drying fruit, and agriculture products, clothes, and carpets.

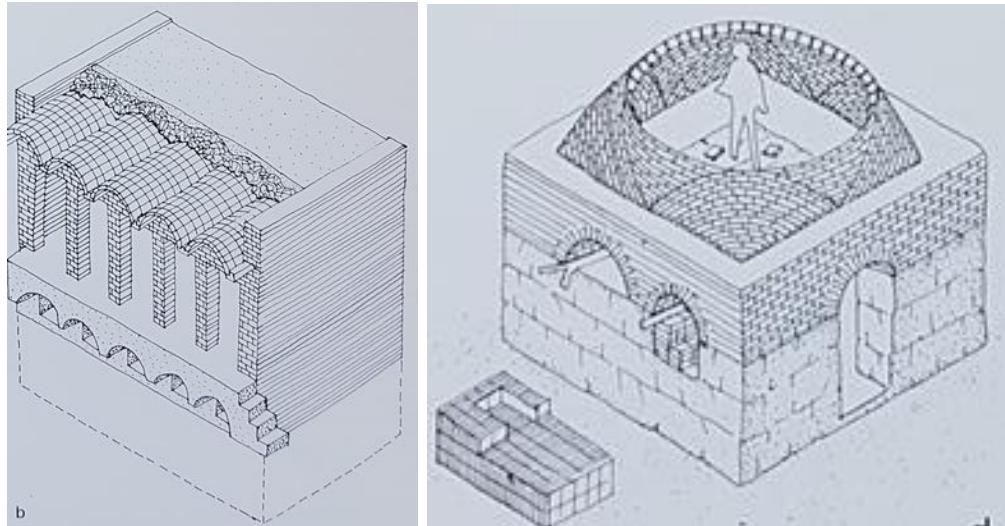


Figure 24: From left to right: roofs with brick and pakhsa walls, a vault and dome (Szabo and Barfield, 1991)

A typical traditional Afghan house has a courtyard with a larger space to the south. The winter rooms are south facing with large openings to obtain maximum use of sunlight during cold periods, and the summer rooms have smaller openings located to the north side. In most cases, there are two kitchens, one attached to the winter rooms, locally called *Taba khana* (see Fig. 25).

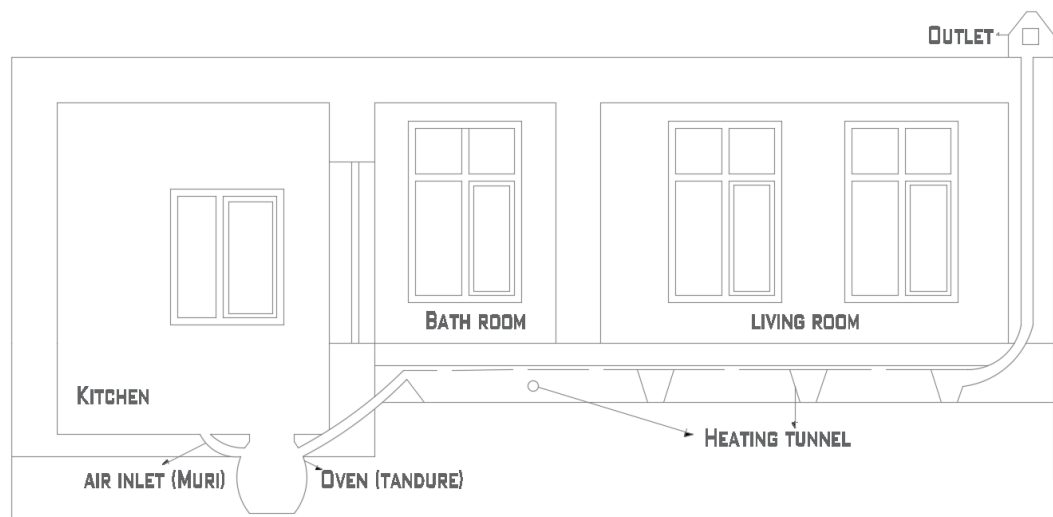


Figure 25: Traditional underfloor heating system modified from Kazimee, (2006)

A clay oven is used to cook bread and circulate the heat through underfloor tunnels made of stone to a bathroom and another room (Kazimee, 2006). Fuel sources for heating the oven are wood, cow-dug, and bush. When the bread cooking finished, the oven is covered with a wood cover; the remaining embers in the oven and the thick raw soil walls keep the rooms warm for long periods, depending on the type of heating source. By contrast, the second kitchen is located inside the courtyard close to northern, western, or eastern walls for the summer period, locally known as *Dalaan*. It is often found that a summer kitchen has a storeroom where the cooking utensils are stored (see Fig. 26). Moreover, in traditional houses, there is a room where the guests stay (see Fig. 25). A toilet is often built adjacent to the wall located to the public road (40 x 50) cm to remove the waste from the pedestrian lane. To provide stability against erosion, the walls and roofs are plastered with a mix of wheat-straw and soil, and the room's interiors are decorated with clay paintings applied by women. While outside the cities, traditionally people keep animals, they are kept in stables altogether: sheep and goat on one side, cows and donkeys on other side, and chickens in the stables; space for grass and straw is located on the top of or beside the stables (Najimi, 2016).

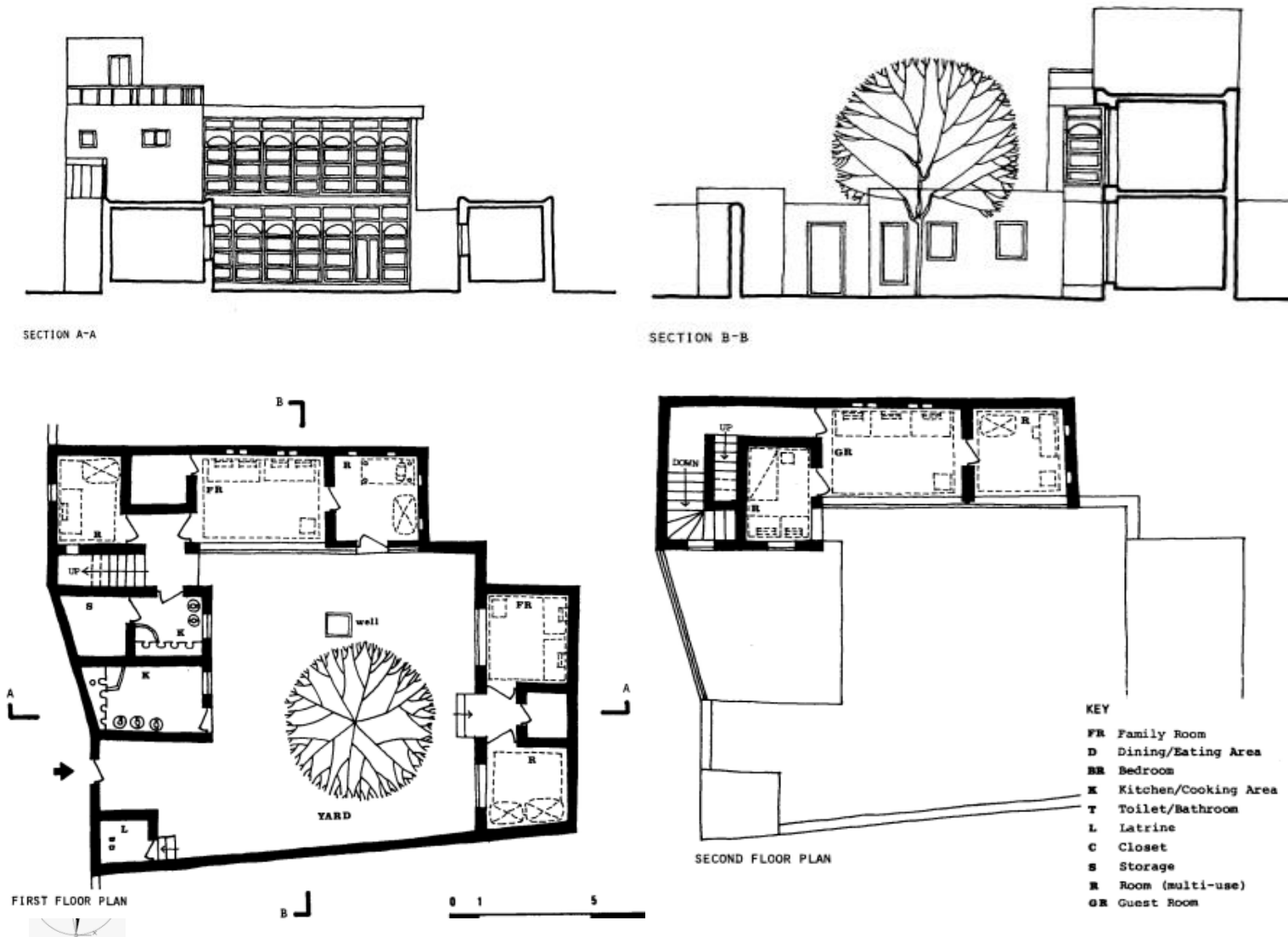


Figure 26: Floor plan of a typical residential house in the old city of Kabul (Kazimee, 1977)

However, there is no national code of practice for building with earth, that is because a mason learns through apprenticeship to complete the construction work for the entire building. Moreover, current research on domestic architecture is limited to Kabul, Nuristan, Kandahar, and Salang in Parwan (Szabo and Barfield, 1991; Hallet and Samizay, 1980; Kazimee, 1977). These papers are mostly discussed in a historic context in terms of the construction materials in those areas. However, they are not presenting geographically the entire country's domestic architecture (Hakim-Ebrahimi and Devillers, 2022). There are provinces with rich architecture, such as in Balkh, Herat, Ghazni, and Ghor. In addition, most of the aforementioned studies do not provide information on the architectural and constructive modes, such as the dimensions and structure of the earth-made buildings (Hakim-Ebrahimi and Devillers, 2022). Therefore, there is a need to geographically study the traditional houses in Afghanistan and find out the detailed architectural and socio-cultural information. For instance, the traditional Herat residential homes with an 'air-catcher', locally known as *badgir*, is a unique construction method. *Badgir* means to have fresh air during hot periods and circulate it inside the rooms (see Fig. 27).

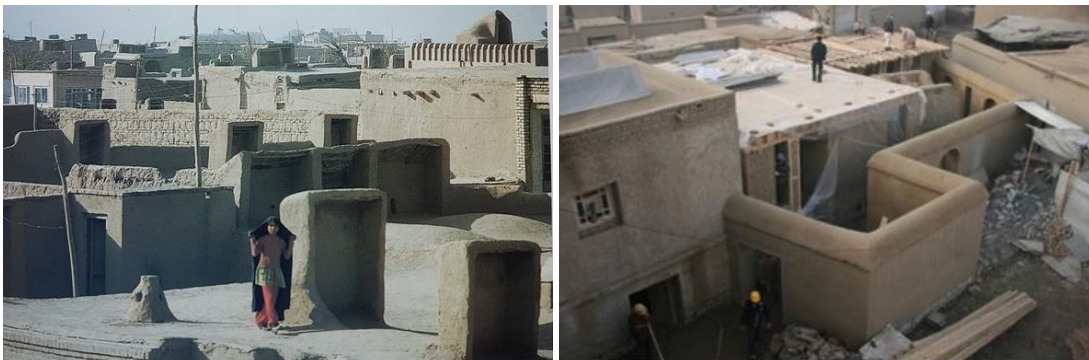


Figure 27: From left to right: flat roofs with brick and pakhsa walls or with badgir (UNFPA, 2015)

1.4.2 Kabul history

Kabul is the historic capital city of Afghanistan since 1775, and it was Babur Shah Mongol's emperor the king's capital in 1502 (Kazimee, 2017). The archaeological evidence shows that Kabul originated from the slope of the Chakari Mountain to the south of Kabul's old city, where Buddhist temples and monasteries were found. In 675 AD, during the Buddhist dynasty, Kabul was an important strategic commercial and pilgrimage centre (Paiman, 2019). At that time, Kabul was protected with defensive walls. In 698 AD, Kabul was invaded by Arabs who captured and occupied Kabul after a few decades; years later, Islam was accepted as the new religion with its novel socio-

cultural values (Kazimee, 2017). In 1502, the Mughal emperor, Babur Shah chose Kabul as the capital of his empire and constructed some beautiful buildings and gardens. Bagh Babour is one of those gardens that still exist. Between the 1500s and 1750s, the territory of Afghanistan was divided between the Iranian Safavid Empire, Turkmenistan, and the Indian Mughal Empire (Hakim-Ebrahimi and Philippe, 2022).

The decline of power in neighbouring India and Iran enabled Ahmad Shah Durrani, a Pashtun commander, to proclaim the Durrani Empire (Malleon, 1879) in Kandahar in 1747. The Durrani Empire was the largest Muslim empire according to its size in the second half of the eighteenth century after the Ottoman Empire. It is also considered to be the founding state of modern Afghanistan, with Ahmad Shah Durrani often described as the ‘father of Afghanistan’. Moreover, as part of this historical narrative, his son, Timour Shah Durrani, was said to have felt closed in in the capital, Kandahar, where he was often aggravated by certain members of his court. To minimise the risk of a rebellion and his possible assassination, Timour Shah Durrani chose Kabul as his capital between 1775 and 1776 (Kazimee and Najimi, 2017). He chose Kabul for several reasons. Firstly, the city had been greatly appreciated by several prior sovereigns who had made it their capital before Timour Shah, such as the Moghol emperor Babur Shah. Moreover, the city has been appreciated for its freshness, being far from the overwhelming heat of Kandahar (Kazimee and Najimi, 2017).

Besides, the city was prosperous, and it was a centre for the arts, culture, and sciences. Its multiculturalism diminished the role of the Pashtuns thirsting for power. Kabul grew fast in this period, and people from the outskirts of city also came to the centre to work and live, mirroring the movements of today. Their livelihood depended on the agricultural land near the city and various trade activities inside the old city of Kabul. In the old city, there were many historic earth-made pedestrian skill quarters, such as Ashiqan wa Arifan, Chindawol, Shur Bazaar, Baghi Alimardan, Murad Khani, and Andarabi. They are named either after tribes or tribal leaders. All these residential areas are typologically very similar and intertwined with bazaars accessible by narrow lanes for pedestrian traffic (Hakim-Ebrahimi and Devillers, 2022).

1.4.3 Morphology of traditional cities

In the Kabul region, the most common constructions are made from sun-dried brick and cob (paksha). Urban houses are usually surrounded by high paksha walls. These buildings often have flat roofs supported by poplar beams. Throughout history, Afghan

cities have played an important role in meeting trade and cultural needs not only for their own people, but also for the merchants and travellers throughout the region. The intensity of trade and the cultural and administrative activities clearly showed the predominance and importance of Afghan cities. These economic and cultural resources, among the richest of their time, influenced the fabric of the city. The old city of Kabul is mainly located south of the Kabul River and includes many historic neighbourhoods that are named after a commercial establishment, a tribe, or tribal chiefs.

In traditional Afghan architecture, with many variations, courtyard houses create the typical urban fabric of traditional Afghan cities with a high population density (Kazimee, 2006). Volumetric features and orientation play a major role in traditional Afghan architecture. A study of traditional Afghan housing has shown that the broadest courtyards are not only associated with the largest houses but are related to the height of the volume on the south side of the house: the ratio of the height on the south side to the north and south width of the courtyard is close to two thirds (Watts, 1981). This ratio is very close to the height of the sun at noon during the winter solstice (see Fig. 28). The penetration of the winter sun at the ground level of the courtyard is probably related to the altitude of Kabul, which in turn affects the amount of snowfall in the winter period. The two-thirds' ratio in the cross-section of habitats implies a strong and direct relationship between man, nature, and built form.

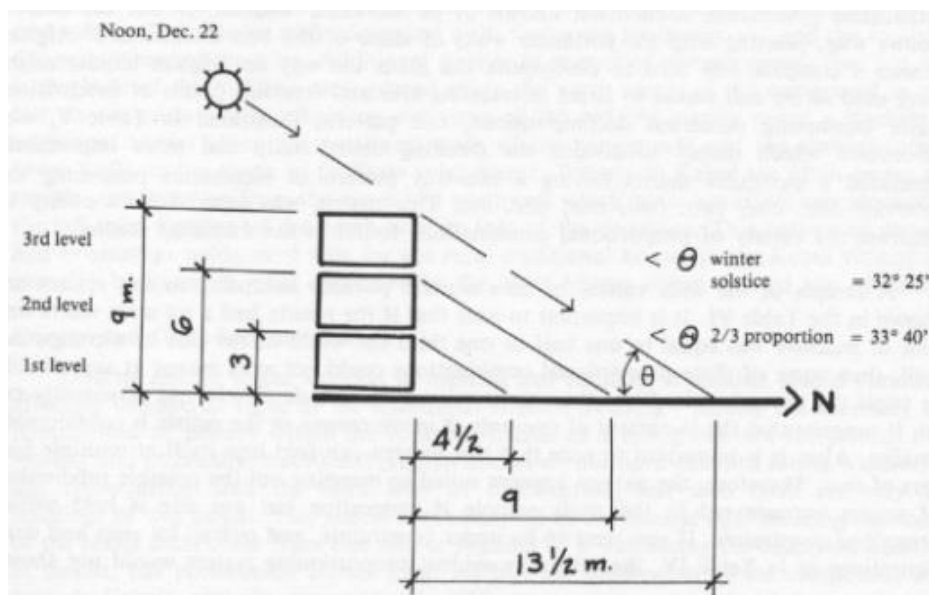


Figure 28: Solar implication of north and south orientation (Watts, 1983)

As a case study, the Murad Khani residential area is described in this thesis. A thorough morphological study of the northern part, the best preserved district, shows that most of the houses are accessible by narrow alleys, oriented east and west, and in some areas covered with second-story habitats; they are served by main streets oriented north and south (see Fig. 29). The size of the houses depends on the wealth and size of the families; most have their main rooms to the south and north of the courtyard, that is the winter and summer rooms. A socio-economical survey was implemented in 2016 and covers forty-two households in the historic district of Murad Khani, representing five hundred and twenty-three people (TMF, 2016); it shows that 39 % of houses have one room (twenty-two households), 27 % of houses have two rooms (twenty-two households), and eleven houses have three rooms. The largest house has seven rooms. The size of the houses varies considerably, ranging from one place housing one household of two people to one abode housing eight households of forty people. According to TMF (2016), the average number of households per house is 1.9, and the average number of persons per dwelling in Murad Khani is 12.4 persons.



Figure 29: Murad Khani (Hakim-Ebrahimi and Philippe, 2022)

To understand the structure, materials, and construction methods, a traditional Afghan house in Murad Khani, a Peacock House, is studied in detail. Winters in Kabul are often severe, and storms often come from the north or northwest but can be blocked by the massive north wall. The following characteristics have been observed of the Peacock House: the north wall is built of sun-dried brick, with a thickness of 70 cm on

the ground floor, and 40 cm on the first floor. The perimeter walls of the courtyard, made of pakhsa, have an average thickness of 40 cm. All the other walls of the house, with a thickness of about 30 cm, are composed of a rough-timber frame with raw-earth brick within the stone foundations that have been laid with earth mortar. The bricks in Peacock House have been laid diagonally in the common parts of the wall and horizontally at the corners. The wooden structure of the staircase ensures the bracing of the house in both directions. This type of framing combined with the use of diagonally laid bricks makes it possible to improve the seismic resistance, compared to a masonry consisting solely of sun-dried brick (TMF, 2016) (see Fig. 30).

The brick walls are finished with a rough clay and straw coating known as Kâh-gel. In the two main rooms, a thin layer of finishing coat, consisting of fine sand, clay, and fibres from the seeds of the Gul-e-lukh¹ plant, are applied over the Kah-gel. This finishing coat, known as Sim-gel, has a white colour, good compression resistance, hydrophobic properties, and a good durability. Examples of such buildings which are over 150 years old in Murad Khani remain in excellent condition and show good resistance (Abdulrahimzai and Hasib, 2018). Almost the entire southern facade is built solely of wood from an eastern tree, known as Archa wood. The finishings on the openings includes frames, arches, and wood panels, meticulously carved. The structure of the two floors and roof consists of circular cross-sectional joists, 75 mm in diameter of raw wood, spaced at 300 mm, which rest on the solid wall on the north side and on the wooden lintel, which is 180 mm in diameter on the south side. These joists have a span of approximately 3.3 m. The floors are composed of short (coarse and semi-circular) wood that rests on the joists to create a deck. A levelling layer of wood chips and other carpentry waste is laid on this deck, followed by a thick layer of soil. The floor covering consists of a smooth layer of carpet-covered earth coating. A smooth layer of earth coating is also applied as a finish on the roof. This type of traditional roof requires biannual maintenance, once before the arrival of winter and a second time in spring, due to the harsh winter conditions. A roof overhang of 80 cm protects the southern facade from solar radiation at the summer solstice, while allowing the dwelling to benefit from solar contributions at the winter solstice (see Fig. 31).

¹ The fibres from the Gul-e-lukh seeds are much finer than those from straw, enabling a smooth surface, completely masking the fibres. The high content of polyphenols ensures long-term natural microbiological protection and makes the coating resistant to mould.

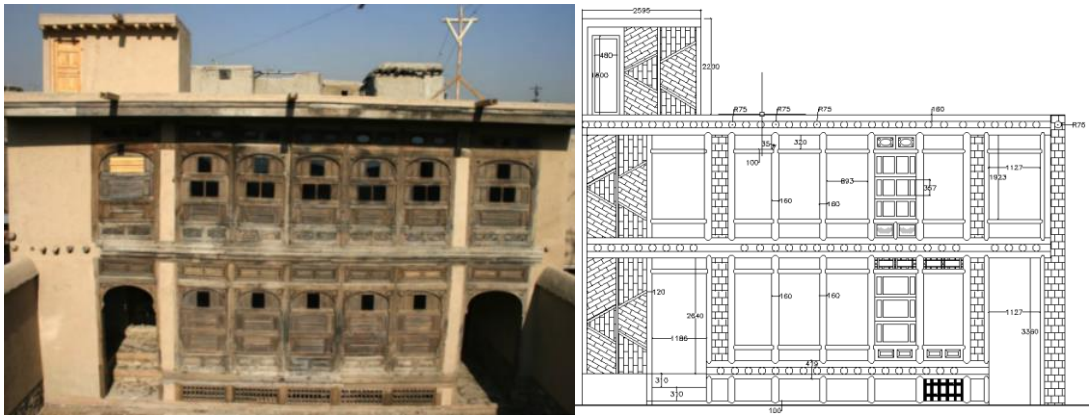


Figure 30: Peacock House photograph and drawings (Hakim-Ebrahimi and Devillers, 2022)

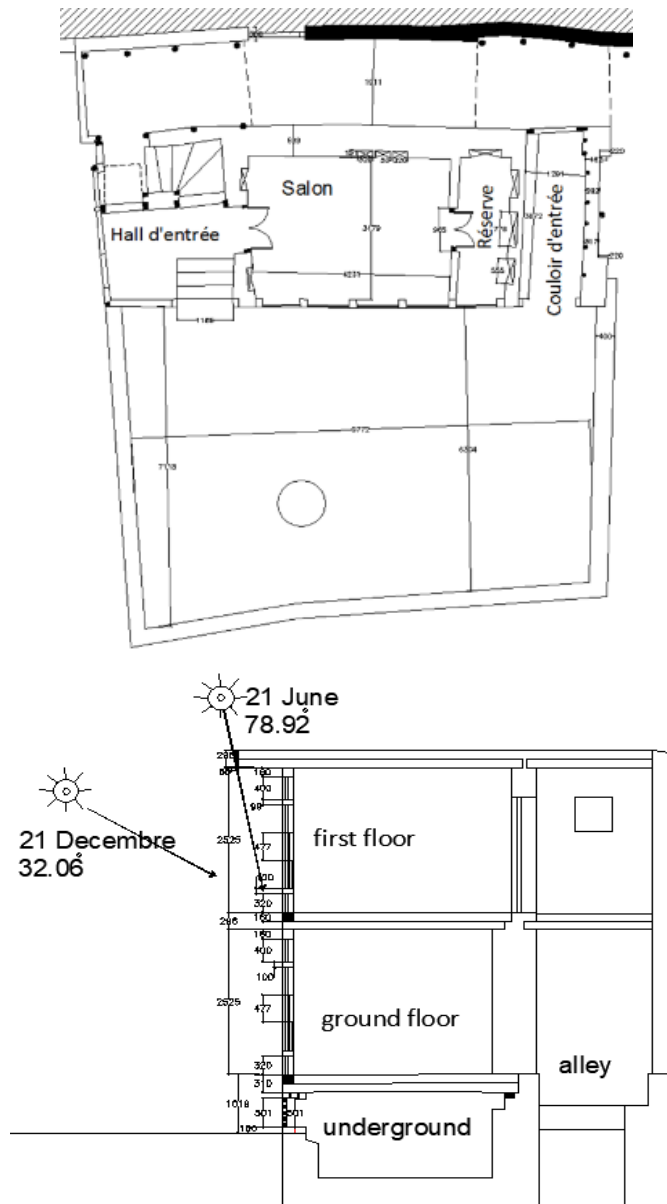


Figure 31: Peacock House bioclimatic section (Hakim-Ebrahimi and Devillers, 2022)

1.4.4 Modern architecture

The development of modern architecture in Kabul started during the 1930s. The city was extended beyond the old city of Kabul. This urban expansion depended on internal migration and economic growth. Further, the city grew during the 1950s and 1960s when the Soviet Union and the USA economically helped Afghanistan with a goal to developing the country (Najimi, 2011). During this time, the government wanted to change the image of Kabul from an undeveloped to a modern urbanised city. In certain parts of Kabul, the existing roads were widened, and new roads were constructed inside the historic area (Najimi, 2011). During the 1960s, the Russians built prefabricated residential apartments, Microrayon, adapted from the Russian word microdistrict (see Fig. 32). They were the first modern residential apartments at the time. In 1966, the Afghan government ordered the Department of Housing to develop a plan and regulate the growth of Kabul and its other large cities. Subsequently, in different parts of Kabul, public infrastructure, buildings, and residential houses were further installed and constructed. Based on this plan, in Kabul, the Khair Khana project was aimed at housing 500 families in the following residential housing blocks: Khoshal Khan Mina, Deh Afghanan, and Karte Naw.



Figure 32: Microrayon prefabricated apartment blocks (Woodbridge, 2012)

Recently, the economy developed rapidly since money was pumped into Afghanistan in 2001 when the US army defeated the Taliban regime and seized control of the Afghanistan government. New and modern materials were introduced in the

construction industry as a demand by foreign clients, troops, and international organisations for constructing on a military basis and for public structures and buildings. Concrete structures, glass facades, various thermal insulation, and electrical equipment were imported into the country. Moreover, this boom in the economy in Kabul resulted in a rapid population growth and greatly increased the housing demand. During the last twenty years, the growth of the informal settlements together with the townships in the city has changed the Kabul into an unrecognisable place. The provision of housing mostly lies in the hands of the private sector.

As part of the housing demand, private townships (a complex of residential and commercial buildings) developed rapidly. Between 2002 and 2012, in Kabul, out of the 85 townships built, 36 were unplanned and not registered with the government (Abdulraqib and Asano, 2014). In 2014, a study on the newly built townships in Shahrak Telayee and Aria was carried out (Hakim-Ebrahimi and Yari, 2014). The findings show that most of the townships have low-quality buildings and structures, and that there are problems with the wall insulation, building orientation, and their lack of green spaces inside the townships (Hakim-Ebrahimi and Yari, 2014). Kouki Mojadidi (2022) is an American and Afghan architect who has implemented socially conscious projects in areas of conflict and natural disaster, leading complex design projects through all phases of development; he has proposed two factors that have severely affected the urban fabric of today's Kabul (Mojadidi, 2022):

- Change in land value and ownership. The new landowners were disconnected from the traditional architecture of Kabul. They constructed buildings with a new foreign vision to obtain more space and increased profits by renting and selling the properties;
- high hopes for a new Afghanistan and the end of the long years of war in the country. Afghans came back from abroad which raised the demand for homes in the suburban area of Kabul.

However, Afghan's construction industry was not able to adapt to the new market; as a result, the construction companies from outside the country benefited from this and migrated to Kabul. Therefore, Pakistani companies won the largest proportion of the new construction opportunities. In addition to the public infrastructure and buildings, they made residential houses with reinforced concrete structures. The modern houses

required more energy compared to the traditional ones; neither added insulation, nor were they connected to a central heating.

During this period, there was a high demand for professionals, such as architects, engineers, and newly graduated students of engineering. There was not a standard code of practice in the country to be able to design buildings in accordance with its regulated and researched principles. Moreover, there was a lack of the required knowledge amongst these young graduates regarding the traditional architecture in the country (Najimi, 2016). Government authorities were unable to provide trainings and seminars to educate these young graduates about the national architecture. Currently, in Kabul, it is difficult to find a good combination of colour, material, height, and form in the buildings (see Fig. 33). There are many examples of more than five-story apartment blocks inside the residential areas where the maximum height is limited to four stories, hence breaching the few standards that exist. In Kabul, many of the historic earth-made residential houses were replaced with five-to -ten story concrete and steel trade centres. Parts of Shur Bazaar, Chindawol, Bagh Alimardan, and Murad Khani are clear examples that are still visible.



Figure 33: View of Kabul in 2019 (photograph by the author)

CHAPTER 2

STATE OF THE ART

CHAPTER 2: STATE OF THE ART

In Chapter 1, the context of the study was discussed. In general, Afghanistan's and in particular Kabul's geography, climate, seismic activity, and architecture were analysed. The objective of the current chapter is to provide information about the importance and history of earth architecture and to analyse the techniques used to build with earth. A further aim is to understand the modern vernacular architecture, and why there is a receptivity toward such architecture. This chapter poses questions as to what the social values and energy demands of these buildings are. Subsequently, it investigates common vernacular housing forms in Afghanistan, such as courtyard and compact housing, which includes the shape of the roofs and ventilation systems. Finally, it makes recommendations for affordable housing in Kabul, Afghanistan.

2.1 Earth construction in Afghanistan

It seems evident that soil was used earlier than any other material for construction purposes. It was not only used for housing, but also for religious buildings and historic monuments. Nevertheless, there is a paucity of research and archaeological evidence to show the exact date when humans started using raw soil for making their shelters. There is some agreement that earth was used in all ancient cultures (Bezerra and Azeredo, 2019); however, there is no consensus amongst researchers on the exact date since some claim that raw-soil construction began during the Agriculture Revolution, 7,000 to 12,000 BCE (Bezerra and Azeredo, 2019). Moreover, Pacheco-Torgal and Jalali (2012) also argue, based on archaeological evidence discovered in Turkmenistan, that the use of earth for building houses began 9,000 to 12,000 years ago. Minke (2012) places it at around 9,000 years ago, providing examples of mud-brick houses in Turkestan, dating from 6,000 to 8,000 BCE. Some believe that raw earth was used during the Prehistoric period (from 1,200 BCE to 2.5 million years ago); further, during the twentieth century, large excavations in central Asia revealed many complex earth-made settlements. It is not clear why in this technological era, it is difficult to find the exact date for the first use of mud as the construction material. Fortunately, there is some consensus amongst scholars that a large number of people lived in these earth-made houses, in 2006 some positing a third of the world's population were living in earth houses (Minke, 2006, 2012) while others have stated 30 to 40 % of the global population (Miccoli et al., 2014), with 50 % from developing countries. Amongst them, in China, 20 million people are proposed to have lived in caves (underground

houses) cut inside the silty soil hills (Minke, 2012). In Islamic countries, nearly all ancient mosques and historic monuments were built with mud brick, cob (pakhsa), and/or rammed earth (RE). However, this subject remains understudied and requires further investigation.

Although, little archaeological evidence is available, it is believed that, the territory where Afghanistan is located dating back to 9,000 years ago (Szabo and Barfield, 1991). This territory was involved in international trading during the Bronze Age (2,000-3,000 BCE) and has helped urban centres such as the Harapan civilisation in the Indus valley, Turkestan, and Iran (Szabo and Barfield, 1991). Examples have been provided of Ashoka, a Buddhist king, who came to Afghanistan, evidenced by some inscriptions discovered in Kandahar. Later on, nomads and cattle keepers captured the country, and this history provides the roots for the Dari and Pashtu languages spoken today (Szabo and Barfield, 1991). However, the recorded history of Afghanistan started in the sixth century when it became part of the Persian Empire. This is mentioned in the Rig Veda (the Sanskrit religious hymns), which describes the Aryan invasion of 200 BCE. Later in the fourth century BCE, Afghanistan was part of the Persian Empire, ruled by Alexander the Great; after his death, other kings ruled Afghanistan during what is known as the Hellenistic period (Szabo and Barfield, 1991). Unfortunately, due to continuous wars, there is a lack of archaeological evidence, thus an absence of recorded documentation. The available studies focused on specific examples that rarely take into account the geographical, historical, and socio-cultural context. These studies focus on Nuristan, Kabul, Kandahar, Herat, and Salang in Parwan. Some examples of earth constructions in Afghanistan are explained in the following.

Cave constructions exist in Bamyan, and Samangan provinces. This construction technique was used widely during the Buddhist period in the mid third-century, but now it is rarely used only in Bamyan (see Fig. 34). In regions with sandstone and conglomerate rock formations, which resist erosion but where it is possible to carve into it with simple tools, caves were built into the cliff faces (Szabo and Barfield, 1991). In some cases, they are extended to the front by a wood and mud roof, and the two sides of the entry were often constructed with masonry or clay walls (Szabo and Barfield, 1991).

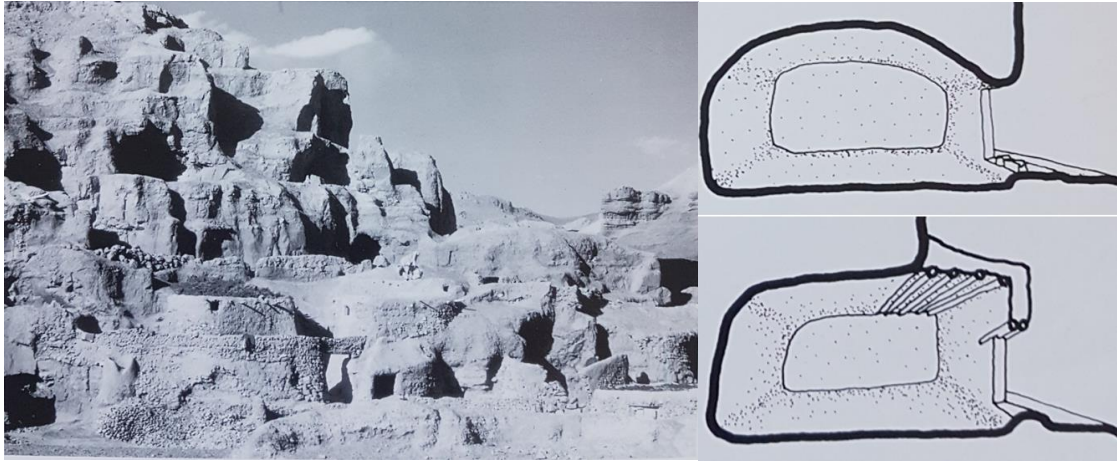


Figure 34: Inhabited caves in Bamyan (Szabo and Barfield, 1991)

Qala, a traditional fortified farm compound built with high pakhsa walls exists in every part of Afghanistan (see Fig. 35). A Qala in square or rectangular form usually stands alone on a flat area; the walls on each side are often 40 to 60 m in length, 6 to 8 m in height, and 1 to 1.5 m in thickness, with four towers (bourges) on the corners rising to 1.1/2 of the walls' height (Szabo and Barfield, 1991). An eighteenth century historic residential courtyard house (Wasay House) located in the Asheqan wa Arefan area was recently preserved by AKTC (2006; see also Fig. 35). It is made from mud-brick and timber frames, with a decorated wood façade, located in Kabul (AKTC, 2006). Before renovation, only the south façade of the original house survived, and the remaining parts and the courtyard were destroyed. The renovation was completed based on the examination of photographs from late nineteenth and mid-twentieth centuries (AKTC, 2006).

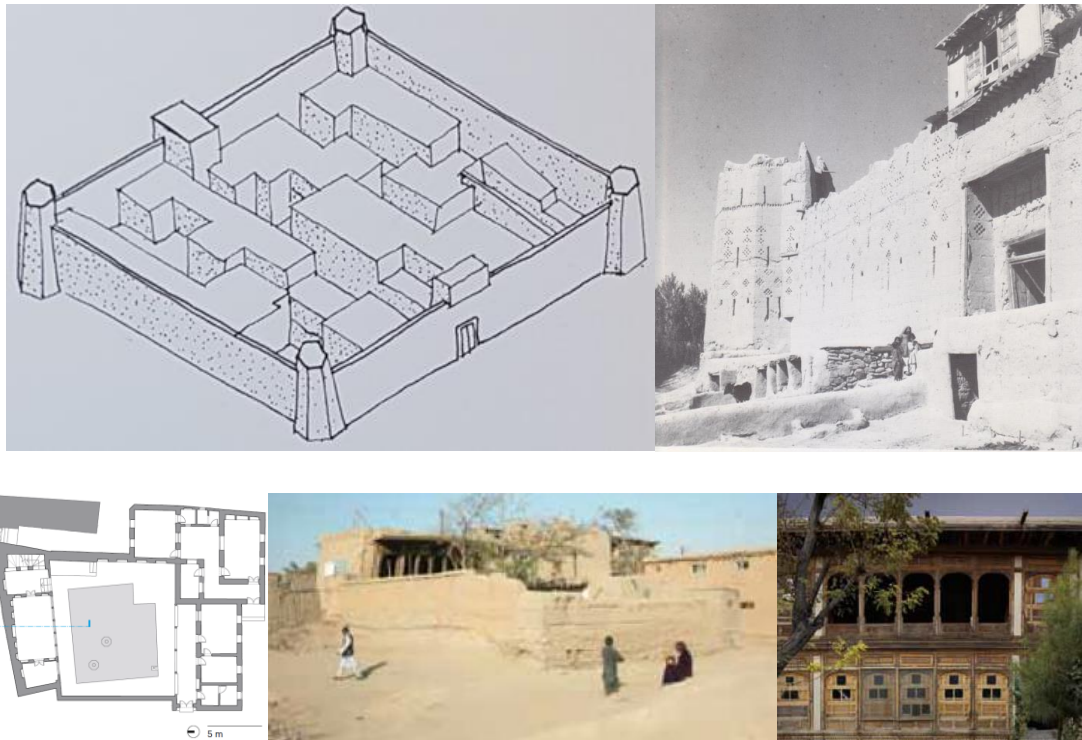


Figure 35: From left to right: earth constructions, two Qalas in Wardak and Wasay House in Kabul (AKTC, 2006; Szabo and Barfield, 1991)

In Kabul, an early-recorded example of earth construction is Babur Garden, built during the sixteenth century. The garden is located in the southwestern foothills of the Sher Darwaza Mountain. In 1607, the construction of the walls around several gardens, including Babur Garden in Kabul, was instructed by Jahangir, the successor of Babur Shah (see Fig. 36). In 2002, when the conservation of this garden began, the remaining section of a wall, made with compacted earth (pakhsa) and up to 8 m high, was found (AKTC, 2006). Other examples of earth architecture are the historic quarters in the old city of Kabul. In the nineteenth century, the areas of Asheqan wa Arefan had many shrines, mosques, public baths (hammams), and courtyard houses (see Fig.37). The mosques and shrines were built with pakhsa and sun-dried brick; the southern façade of these buildings was decorated with wooden columns, beams, and windows.



Figure 36: Babur Garden before and after renovation (AKTC, 2006)



Figure 37: From left to right: entrances to the Asheqan wa Arefan Shrine, Goldasta Mosque, and Chuqurak Mosque (AKTC, 2006)

In Nuristan, an isolated region like the eastern mountains of Afghanistan, close to the Afghanistan-Pakistan border, there is a scarcity of arable land; therefore, it is preserved for agriculture, and houses are built on the hillsides (see Fig. 38). Generally, houses are built up to two to three stories high, where the ground level is used as storage and stables for animals, and the upper floors are for familial daily life (Kazimee, 2009). Homes are made from wooden structures with stone and earth, accessible through verandas; the wood for construction comes from the mountains near the villages (see Fig. 38). The flat roof of one house serves as the patio for the above neighbour (Kazimee, 2009).



Figure 38: View of Nuristan Valley homes and veranda (Kazimee, 2009)

Examples of high-stonewall and flat-roof constructions are found in the mountainous region of Salang. The walls are thick (600-800) mm, with a few small windows to better insulate the inhabitants (see Fig. 39). The stones were either laid dry or with clay mortar and filled with clay from the interior, and occasionally from the exterior, acting as a windbreak; in the corner of the walls, long pieces of wood were applied to affect the lateral stability (Szabo and Barfield, 1991).

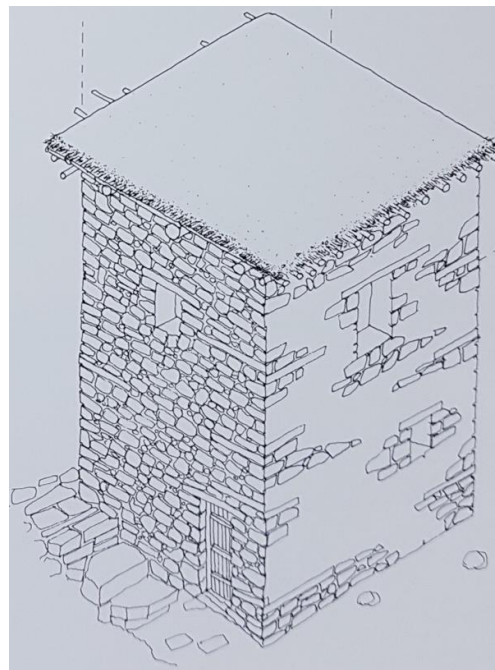


Figure 39: High stonewall house in the Salang Mountains (Szabo and Barfield, 1991)

2.2 Construction techniques

There are a variety of construction techniques available. Different cultures use its local and available techniques, which mostly reflect the identity and culture of that location. Within this variety, there are traditional methods that have been used for years and passed down from generation to generation. Moreover, they have been used extensively, especially in developing countries for constructing homes, religious

monuments, and cultural buildings. However, recently, some modern methods have been developed, which are mostly used in developed countries. These modern methods are responsive and applicable to the mass construction of housing; such modernised techniques enable the industrialised production of earthen elements, such as CEB and prefabricated RE, thus reducing cost and time.

2.2.1. Traditional methods

2.2.1.1 Sun-dried brick

There are different names used for brick in various places, such as sun-dried brick, earth block, and adobe. Adobe is taken from an Arabic word called Attob, which means sun-dried brick (Pacheco-Torgal and Jalali, 2012). Adobe has been used for thousands of years, almost with the same shape and composition (see Fig. 40). Traditionally, this technique together with pakhsa has been used for the construction of houses and courtyard walls. The Peacock House is a good example in Murad Khani, Kabul (Hakim-Ebrahimi and Devillers, 2022).

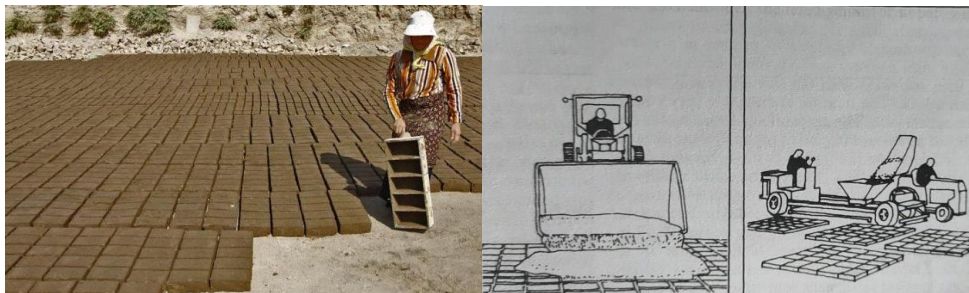


Figure 40: From left to right: sun-dried brick manual and machine production (Auroville Earth Institute, 2020)

2.2.1.2. Pakhsa

Pakhsa is a well-known earth construction technique in Afghanistan; in this method, raw soil in a plastic state is compressed by either human or cow feet and/or tractor tyres to give it an extra compressive strength and durability (see Fig. 41). Subsequently, it is applied by a skill labour to the walls. After 24 hours of the pakhsa application, two sides of the pakhsa layers are cut with a steel cutter to level the surfaces. A day prior to application of the second layer, soil-straw plaster is applied on the top of the pakhsa to cover the cracks created in the last 24 hours. Moreover, the drying period of the pakhsa layer takes 3 to 5 days before another layer can be applied.



Figure 41: Preparation of loam and construction of pakhsa walls (photographs by the author)

2.2.1.3. Rammed earth (RE)

Rammed earth (RE) represents another well-known traditional method of building with earth that historically exists around the globe. Similar to sun-dried brick, for RE, different names have been provided: in France it is called *pisé*, in Spain *barro apisonado*, and in German *stampflehmbau* (Minke, 2006). Examples of RE foundations have been found in Assyria, dating from 500 BCE (Minke, 2006). In this technique, (15 to 20) cm layers of moist earth are poured into wooden or steel frameworks and compacted layer by layer to form the wall (see Fig. 42). Once a layer is complete, the framework is extended above, and the second, third, and subsequent layers are applied. Traditionally, rams are used to manually compact the layers, which consumes time; however, now it is possible to apply electric and pneumatic rams to compact the layers.

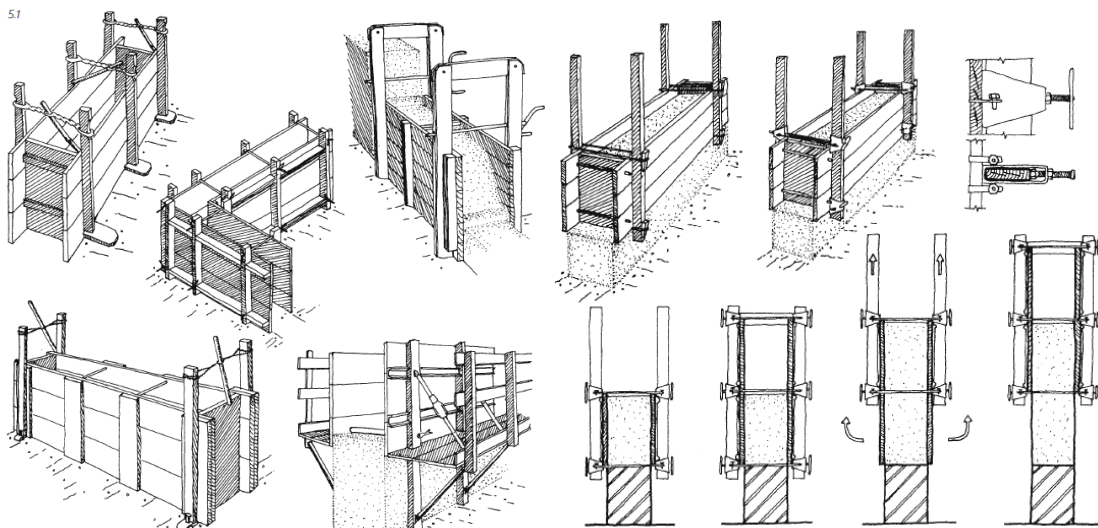


Figure 42: Wooden framework application in stages for RE construction (Minke, 2006)

In RE, with 10 % cement, a compressive strength between 5.5 and 13.3 MPa, depending on the type of soil, mineralogy, and particle size distribution is achievable (Porter et al., 2018). This can increase by augmenting the percentage of cement used. Porter and his colleagues (2018) further tested RE against erosion with two stabilisers, and the following results were achieved: RE with a lime stabiliser for a wall 20 years after it was built shows 2 mm erosion compared to a non-stabilised RE with 6.4 mm erosion in the same period. Further, a test of cement stabilised with RE was performed with a waterjet with non-measurable erosion, while without stabilisation, RE did not last for more than one hour (Porter et al., 2018). It is, nevertheless, possible to state that the stabilisation of raw soil with cement is not environmentally efficient. By contrast, alternative methods can be used to protect the exterior wall from erosion; the use of soil-straw plaster is a common practice in developing countries; further, by using the ceramic pieces of each layer of RE, indicated by Martin Rauch (cited in Heringer et al., 2019), these methods can protect the wall from rain, frost, and the sun, and it can extend its longevity.

2.2.1.4. Wood structure with brick infill

This technique is used in various parts of Afghanistan. In Nuristan, all residential houses are made with this method; vertical and horizontal loadbearing wooden structures are infilled with stone and clay (see Fig. 43). In Kabul, the ancient houses were made with this technique. Peacock Houses in Kabul are an example of this type of construction (see Chapter 1). The north wall of the house is 70 cm thick at ground level and 40 cm on first floor; the southern wall is made of decorated timber and sliding windows. Other walls have a thickness of about 30 cm, are composed of rough-timber frames, with a sun-dried brick infill, and have been laid with soil-straw mortar (see also Fig. 43). The bricks are laid diagonally in the centre of the wall and horizontally at the corners. This type of framing combined with the use of diagonally laid bricks makes it possible to improve the seismic resistance in contrast to houses consisting solely of raw-earth brick (Hakim-Ebrahimi and Devillers, 2022).

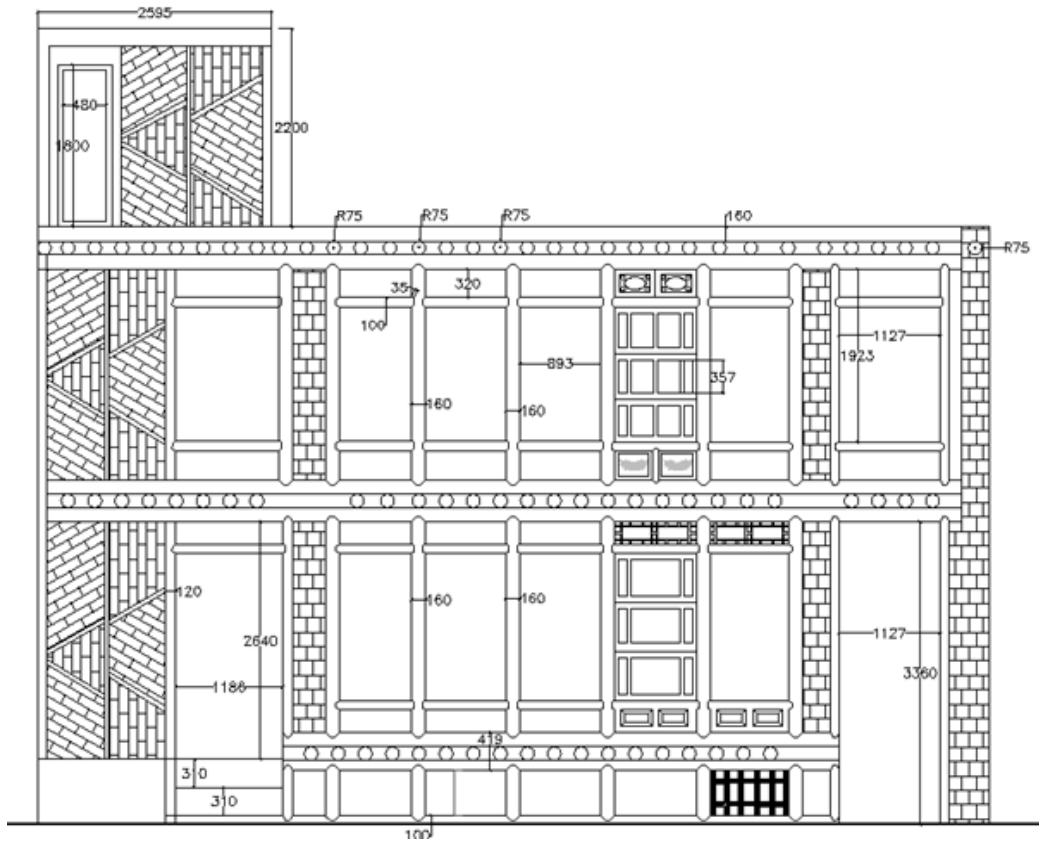


Figure 43: Wooden structure with brick infill in Peacock House (Hakim-Ebrahimi and Devillers, 2022)

2.2.2. Modern methods

Modern earth-construction techniques consist of the following materials: CEB, prefabricated rammed earth (PRE), and poured earth, which are discussed below.

2.2.2.1. Compressed earth block (CEB)

In recent decades, with new improvements in materials, engineering a form of CEB has been developed. There are also compressed stabilised earth blocks (CSEB), which are stabilised by adding binders, such as cement, lime, fly ash, and wheat straw. The decision as to which stabiliser to use mainly depends on the type and mineralogy of the available soil. For example, when there is more sand and gravel, cement is a good stabiliser while soil with more silt and clay is better stabilised by hydrated and natural lime (Minke, 2006). To prepare CEB, a good design mix is essential, consisting in the required amount of sand, silt, and clay, and with the optimum moisture content (OMC). The mixed material is added to a steel press to compress it manually or with an automatic machine (see Fig. 44). After extracting it from the press, the CEB is air-dried; however, for CSEB, curing is also necessary to obtain a good compressive strength. A minimum of a 14-day period is required, although a 28-day period is better, for the curing; plus, the appropriate levels of humidity are also required to obtain the

preliminary strengths (Houben and Guillard, 2014). This could be achieved by keeping them under plastic sheets, to prevent damage from the wind, maintaining a relative humidity, and/or pouring water on a daily basis onto the blocks. The colour and appearance of the blocks depend on the type and content of the minerals in soil. When the clay contains chemical compounds such as hydrated or other iron oxide, this gives a yellow or red colour to the clay (Minke, 2006).



Figure 44: From left to right: manual press block machine (photograph by the author) and automatic block press CLU 3000 (Minke, 2006)

2.2.2.2. Prefabricated rammed earth (PRE)

Prefabricated rammed earth (PRE) has developed from traditional RE techniques. The advancements in modern RE methods have occurred over the last five to six decades, mainly in developed countries such as the USA, Australia, and countries in Europe, but also in India and Sri Lanka (Reddy and Kumar, 2010). A large wall is made in a factory and cut into smaller walls, using a saw, and then transferred to the construction site for installation. This technique could be described as a reaction to today's conventional building construction; the wall is produced, cured, and dried in the production hall under the supervision of professionals who provide and monitor the quality. It is possible to make a wall with more than one layer, where part of the wall works as a loadbearing structure and another as insulation (see Fig. 45). With this technique, there is no need for space on a construction site, and the building duration will significantly decrease. Martin Rauch, the Austrian founder of Lehm Ton Erde Baukunst (loam-clay-earth), is famous for his earth architecture and PRE wall productions (see also Fig. 45). Some example buildings from the three materials Lehm, Ton, and Erde or loam, clay, and earth in Europe are as follows (see also Fig. 45): (1) Studio Rauch in Austria (1990-1994); (2) Vinery La Raia in Italy (2005); (3) Ricola Herb Centre in Switzerland (2012/3); and (4) Alnatura Campus in Darmstadt-Germany (2017).

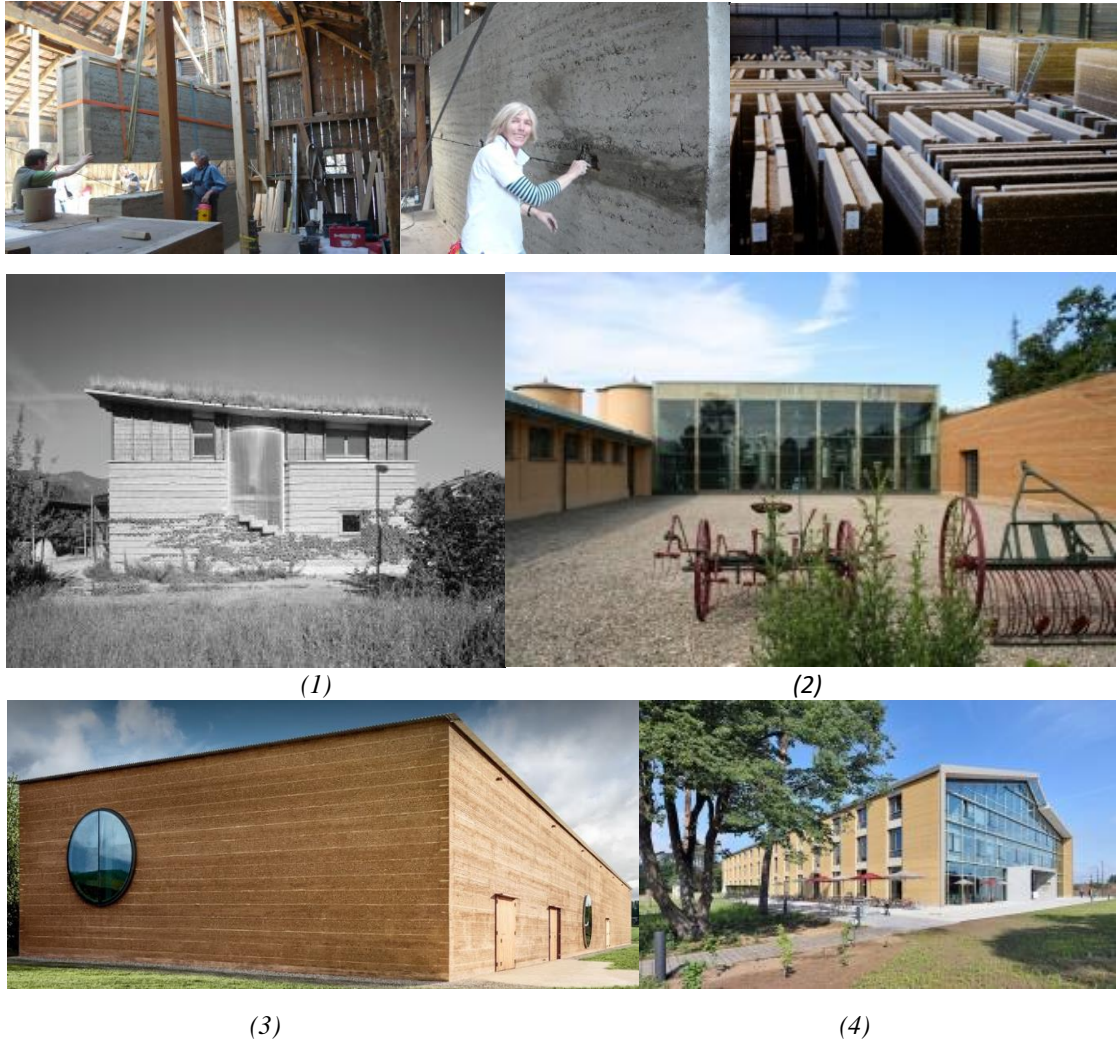


Figure 45: From top left, middle, to right: installation of PRE wall and insulated walls; (1-4) PRE walls and sample RE buildings in Europe (Rauch, 2022)

However, if the surrounding walls are not stabilised, then precaution is required to protect the exterior walls from the environmental effects of erosion. This is addressed by either the use of soil-straw plaster (see Fig. 46), which is a common practice in developing countries, or by using Martin Rauch’s ceramic pieces (see also Fig. 45) on each layer of the RE walls (Heringer, 2020). These methods protect the wall from all weather conditions.



Figure 46: From left to right: traditional plaster in Kabul (Peacock House) and RE wall protected by ceramic support (Heringer, 2020)

2.2.2.3. Poured earth

Poured earth is a modern method of using raw soil for building vertical walls and horizontal slabs, similar to RE constructions, but without the use of compacted force. For producing the poured-earth elements, the same technology as for ceramic and concrete are used. In this technique, in addition to cement and chemical additives, the use of a plasticiser is important to reduce soil viscosity and permeability. Compared to RE, it is possible to obtain identical results with poured earth and for the optimum moisture content (OMC; Habert, 2016). Her study showed that with 1 % superplasticiser, 5 % calcium sulfoaluminate cement (CSA), 0.25 binder/water ratio, and a 90-day drying period, a compressive strength of 8 MPa can be achieved. The findings show that (see Fig. 47) with the same percentage of cement, the increase in water can significantly decrease the compressive strength (Habert, 2016). Ronsoux et al. (2014) used two polymer additives (sodium hexametaphosphate and sodium salt of polyacrylic acid), and their findings show that by adding a small amount of these additives (0.5 %), it can greatly reduce the viscosity and yield stress of dilute soil suspension. In the case of mortar, its use results in using less water, which in turn reduces the drying period and provides better compressive strength (Ronsoux et al., 2014).

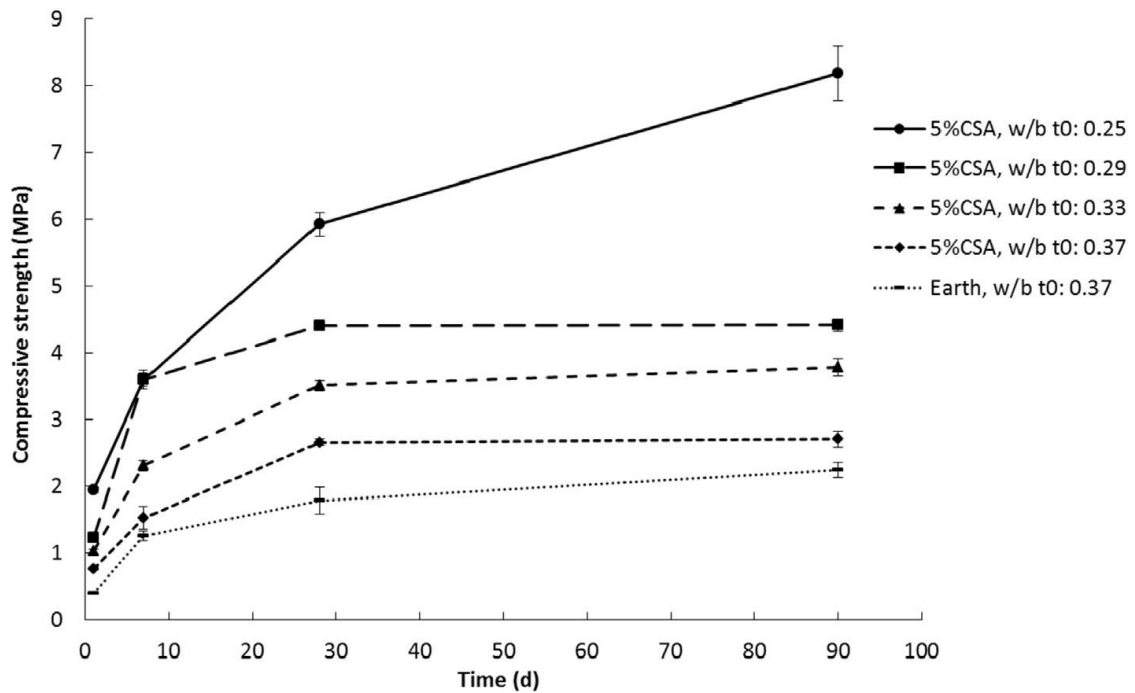


Figure 47: Compressive strength over time: samples with CSA contained superplasticiser (Habert, 2016)

2.3. Common vernacular housing forms in Afghanistan

There is no unique national architecture that could represent Afghanistan as a whole. Different regions have their traditional architecture and construction techniques, which depend on the locally available materials. However, in this section, some of the common housing forms, roof shapes, and ventilations systems are discussed.

2.3.1. Courtyard houses

In traditional Afghan architecture, the type of housing that has been argued to fit the distinct social and cultural requirements is the inner courtyard house. With many variations, courtyard houses create the typical traditional Afghan architecture in the highly populated cities (Kazimee, 2006). Traditionally, the majority of Afghans were living in courtyard houses; in addition to their environmental impact, the courtyard housing design encourages the privacy of the family who lives within. Courtyards are locally called *hawili*, which include the building and its open spaces. In reality, the courtyard is not only private and protected, but it also has other usages. For example, during summer, traditionally it was the women who would cooking bread and meals in the summer kitchen or *dalaan*, the family has breakfast and enjoys the morning and evening fresh air, and they sleep at night on a *sakooncha*, a flat platform usually 60 cm higher than ground level, in front of the building (Kazimee and Mcquillan, 2002) (see Fig. 48). The courtyard includes a water-well, trees, and sometimes a swimming pool;

it is a place where young girls who are not going outside can play and learn traditional crafts, such as carpet-making, sewing, and fancywork (Kazimee and Mcquillan, 2002). In Kabul, traditional courtyard houses have 1 to 3 stories with a square or rectangular shape. The courtyards are isolated from the outside by four walls, and there are rooms with an overhang on the south-faced wall, a summer kitchen, and a veranda (normally a covered space), which is protected from the sun and rain (Sharifzai et al., 2016). It is believed that the courtyard house was developed from of Qala, often found on the outskirts of cities, for one large extended family, with a shared guest house, waterwell, mosque, and stables. Conversely, the courtyard is for single families or less.

A study by Sharifzai et al. (2016) found that currently more than 95 % of Afghans live in courtyard houses for the following three main purposes: 1. They serve as a secure private and open space for family members, especially women and children; 2. during the summer, the surrounding four walls provide shade to the inner rooms, which keeps them cool during the day, and during the winter, it prevents the cold temperatures and wind from entering; 3. In some cases, one courtyard is used by multiple families, and the surrounding walls maintain their privacy as well as providing protection from the outside. Sharifzai et al.'s (2016) study further shows that two types of courtyard houses exist: traditional and contemporary. Depending on the house, in view of these traditional designs, courtyards are surrounded with rooms connected to the courtyard walls on the north, south, east, and west, while some have rooms on two or three sides. The rooms have independent connections to the courtyard through the doors and windows.

However, modern courtyard houses have rooms on the south, but in some cases, they may be extended to the east or west (see Fig. 49). In Kabul, this modern type of courtyard house was introduced during the 1970s by the Afghans who were educated in Europe or the USA (Ayoobi and Lu, 2021). The developed and modern parts of Kabul, including Shahr-e Naw, Wazir Agbar Khan, and Karte Naw, already have such housing. The courtyard layout concept in traditional architecture reinforces the respect for cultural values and the preservation of family ties, which is often destroyed in modern architecture designs and layouts, since they lack social interaction spaces (Femi and Arenibafo, 2017).

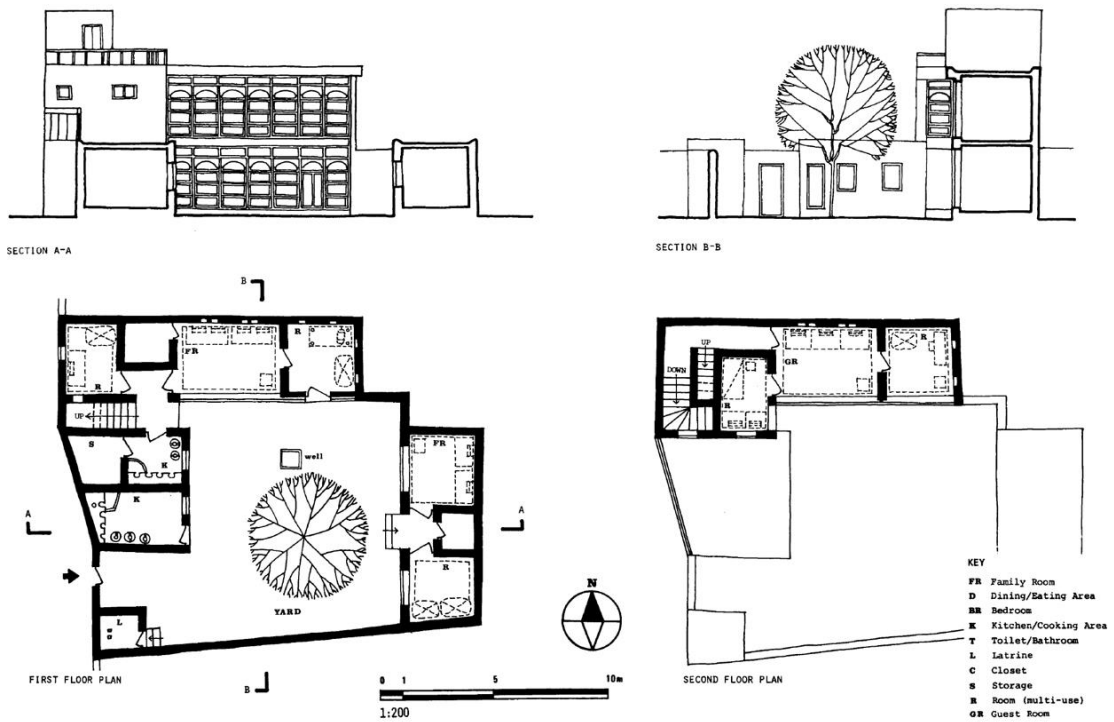


Figure 48: Plan and sections of a traditional courtyard house in Kabul (Kazimee, 1977)

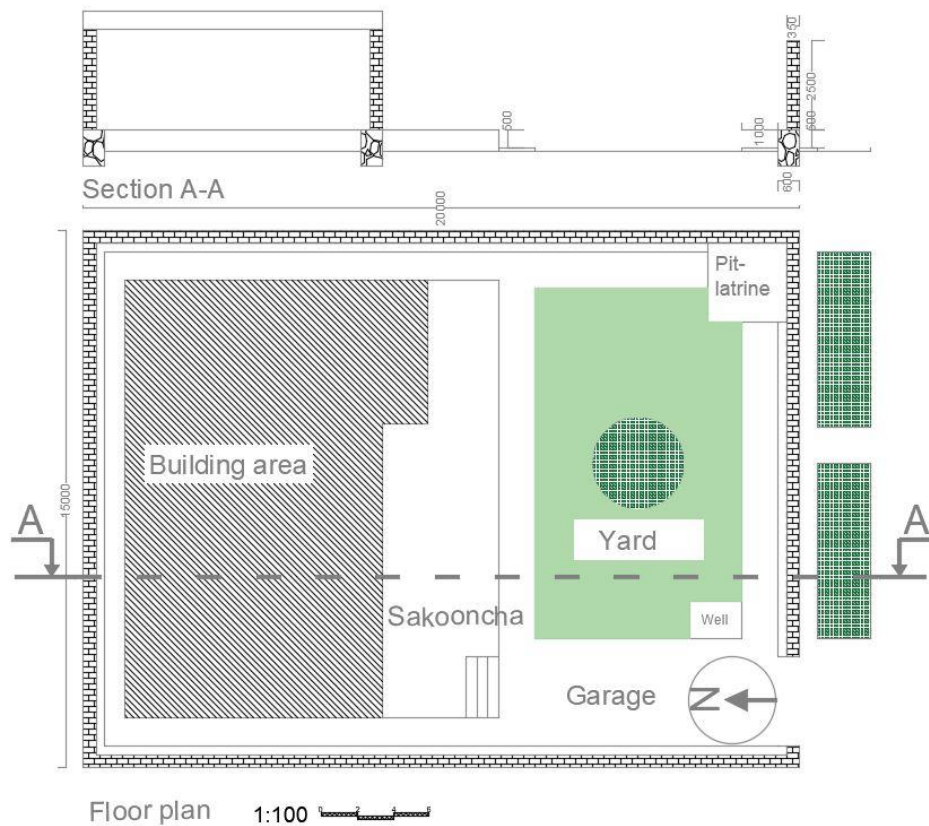


Figure 49: Plan and section of a typical modern courtyard house (drawing by the author)

2.3.2. Compact housing

Compactness is a term used to measure the numbers of dwellings per land area in hectares or acres. Based on the number of houses and land used, areas are classified as low, medium, or high density, which in turn has a direct effect on the cost and energy demand of the units. Building density can affect the overall sustainability. The more compact an area is, the more it reduces the total cost of the dwelling, also requiring less land, transportation, infrastructure, and smaller houses (Asfour and Alshawaf, 2015; Kazimee, 2008). These characteristics and environmental efficiency are visible in the vernacular architecture of Afghanistan as the dwellings can be categorised by their compactness, form, efficient land use, and building ecology (Kazimee, 2008). Mostly the traditional houses in the country are pedestrianised, energy efficient, and constitute unified complex buildings that show the rich cultural history (Kazimee, 2008). In Kabul, these characteristics are visible where residential buildings are accessible via pedestrian walkways and cycle routes, thus improving the overall interaction in the community (see Fig. 50).

The UNFPA (2015) survey in Afghanistan found that the total built up area in Kabul was 40,142 ha, the total numbers of dwellings was 396,095, and the residential area counts for 17,335 ha. The urban density in Kabul is 9.8 dwellings/ha, and the number of people is 74-89/ha. The residential density is 23 dwellings/ha, with 171-206 persons/ha, where 7.5 to 9 people live in each unit (UNFPA, 2015).

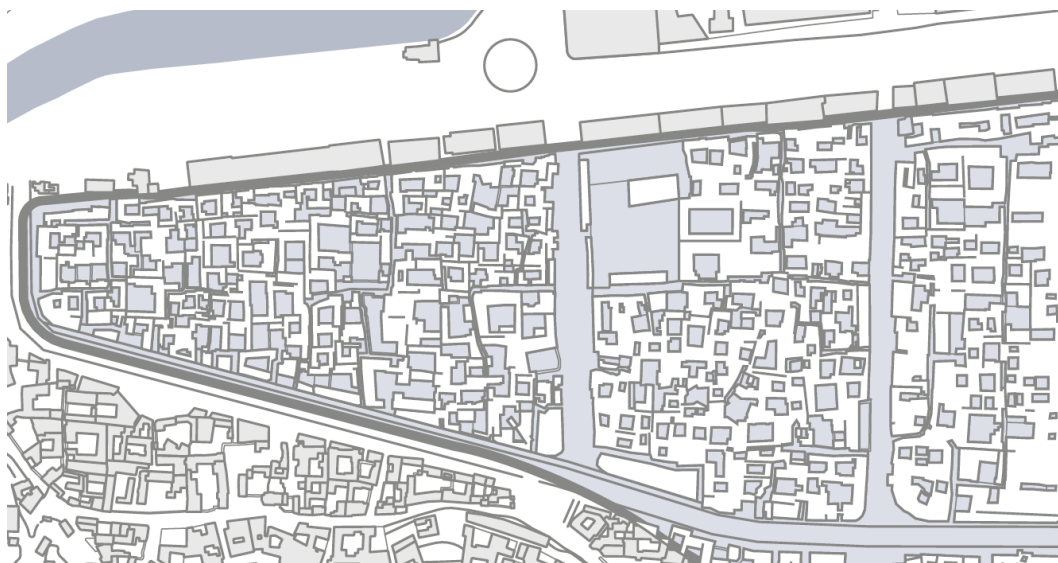


Figure 50: Kabul (Chindawol) pedestrianised residential area (AKTC, 2006)

2.3.3. Common roof shape design

Depending on the availability of local materials, techniques, and the location of the building, roof shapes vary in various parts of Afghanistan. Sun-dried brick is a well-known traditional roof-building material in the southern and western parts of the country, where brick is used for the dome and vault roofs. This type of square and rectangular shaped roof (see Fig. 51) is built on top of a massive brick or pakhsa wall (Szabo and Barfield, 1991). In the southern Kandahar, curved roofs built on the top of high walls are common place. Two forms of curved roofs exist (see also Fig. 51): with singular curves, covering the entire roof, or a few small curves located side by side (Szabo and Barfield, 1991). In contrast to the flat roofs, domed, vaulted, and curved roofs require more work and skilled labour.

However, there is a flat-roof prevalence in all parts of the country for both courtyard houses and Qalas (Szabo and Barfield, 1991; Hakim-Ebrahimi et al., 2022; Hallet and Samizay, 1980; Kazimee and Mcquillan, 2002; AKTC, 2006; UNFPA, 2015). It is simple to build a flat roof on the top of poplar wood, steel, or wooden beams. Flat roofs attached to each other have multiple usages (see also Fig. 51): covering a room, providing outdoor living spaces during the summer, drying fruit and agricultural products, and washing and drying clothes and carpets (Najimi, 2016). In Kabul, only the flat roofs are used for traditional and modern housing.

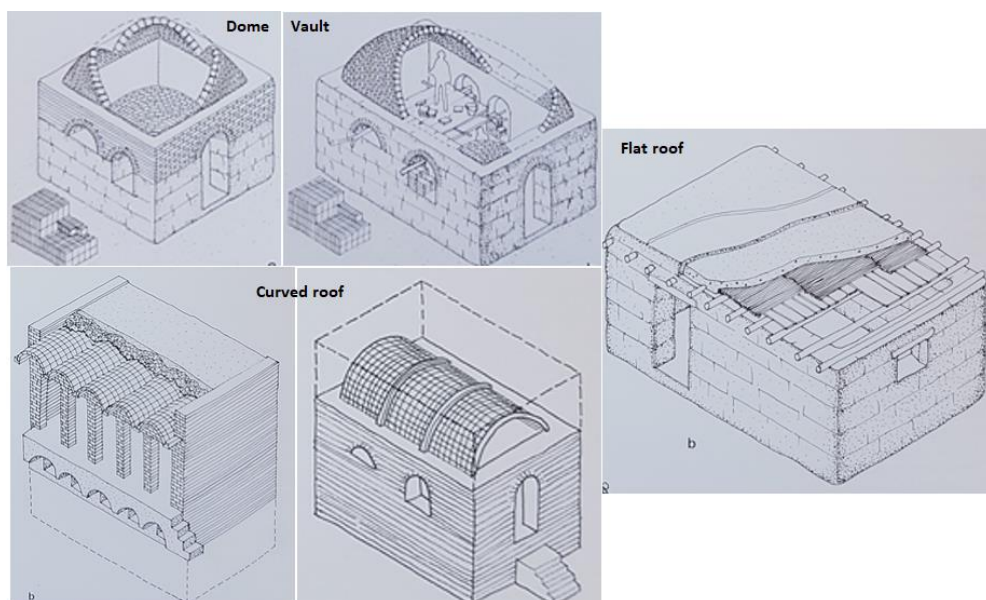


Figure 51: Various roof shapes in Afghanistan (Szabo and Barfield, 1991)

2.3.4. Natural ventilation

Ventilation is one of the common systems that brings fresh air into homes. Natural ventilation means getting the air flow inside the house without using energy and mechanical systems. When natural ventilation is integrated with thermal masses, that is the materials that store thermal energy, it can provide passive cooling systems and maintain the internal comfort of the building. Ventilation is mainly used for the following three purposes: improving the indoor air quality, cooling, and cooling the thermal masses in the building (Zhou et al., 2008). Many factors affect natural ventilation, such as building orientation, position, size, and the type of openings designed. Hassan et al. (2007) have investigated the effects of such factors: orientation, location, and size of the openings. They have used flow visualisation and computer analysis to determine the causal relationships involved. Their findings show that the positioning of building is important for better airflow inside the building. They further demonstrated that with two openings, better ventilation is obtained. In single-sided ventilation systems, with two adjacent windows, it does not matter where a wall is positioned; with two non-adjacent openings, it generally provides enhanced ventilation than having two adjacent ones (Hassan et al., 2007).

In Afghan architecture, the use of natural ventilation is common. This system has been culturally practiced for years principally because most do not have access to electricity to use mechanical ventilation. For affordable housing in Kabul, cross-natural ventilation systems seem to provide an essential solution for obtaining and maintaining fresh air inside the houses. For this, the wind direction is also important, thus the openings need to be located accordingly for a robust ventilation. Kabul has a complex topography, which affects the wind speed and direction. A study on Kabul airport has shown that from May to September, this area experiences high-speed winds (7 mile/hour). From May to October, the main wind direction is from the north (see Fig. 51), and for the remaining 6 months, it is mainly comes from the west (Weather Spark, 2022).

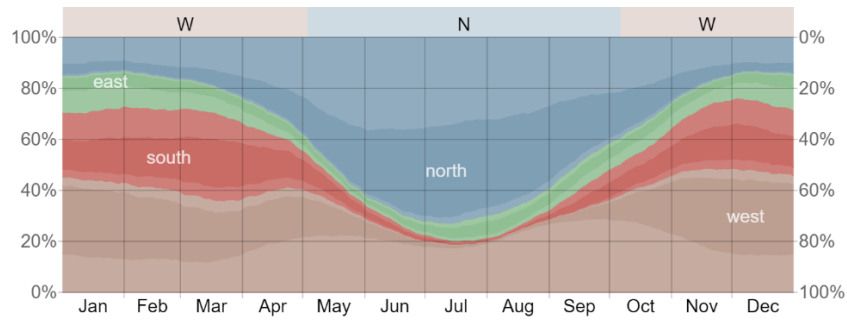


Figure 52: Wind direction for Kabul (Weather Spark, 2022)

Kabul's wind direction can help the design of cross-natural ventilation systems; for instance, the wind flow is from the north in summer, when ventilation is in high demand. Therefore, cross-ventilation systems with openings to the north and south to enable low-cost housing seems to be an ideal solution. Designing small windows (inlets) in the northern wall to welcome the wind and larger ones (outlets) in the south wall for the wind to leave could help to cool the house and provide an excellent internal air quality. An experiment by Fathy (1978) in Egypt shows that when the area of the outlet/(area of inlet) is equal to 2, the amount of wind passing through the room is 113.3 m³ p. h., and any increase in the area of the outlet enables more wind to pass through. When the area of the outlet/inlet is equal to 3, 4, and 5, the amount of wind passing the room is equal to 120.3, 123.1, and 124.6 m³ p. h., respectively.

2.4 Modern vernacular architecture

When the term modern vernacular architecture is employed, this thesis is referring to the capacity of traditional architecture, and how it can be redefined through the use of modernised knowledge on mass-construction techniques. With the same local material, the question remains as to how to construct modern designs with increased comfort in the buildings. Further, how is it possible to minimise the labour on building sites? This is because traditional methods of construction require more labour, time (Pacheco-Torgal and Jalali, 2012; Walker, 1997), and money. Thus, how is it possible to minimise building energy use while maintaining levels of comfort? Finally, how is it possible to reduce building construction labour, time, and money? All of these questions can be answered by the use of modern vernacular architecture. Modern vernacular architecture consists in new methods, local materials, and the capacity of an architect to coordinate the work (Frey, 2010).

Vernacular historically derives from Roman law, meaning products that were homemade or homegrown, and which were not sold in the market (Frey, 2010). With

this definition, it implies a working and living locally, thus enhancing a local sense of community as reminiscent of traditional ways of living. Unfortunately, this is lost in today's climate in most areas of the world. Modern vernacular architecture not only maintains traditional ways of life, but it also prevents draining local money into the pockets of international companies that produce these modern materials, such as concrete and steel (Heringer, 2020).

In Afghanistan, there is a lack of awareness amongst architects and engineers about the traditional architecture in the country (Najimi, 2016) and limited professional knowledge about modern vernacular architecture since it is not common practice. Nonetheless, there are a few modern vernacular projects that have been built between 2005 and 2012 by foreign architects and organisations. Anne Feenstra, a Dutch architect and owner of AFIR Architects, built Band-e-Amir National Park Visitor Centre and maternity waiting homes in five different provinces in Afghanistan (AFIR-Architects, 2011, 2022). In addition, Maria Garzia Cutuli Primary School in Herat constitutes another example, which was built in honour of the Italian journalist who was murdered by a group of gunmen in Afghanistan in 2001 (Arch-Daily, 2022). These two projects are discussed in further detail below:

1. Band-e-Amir National Park Visitor Centre is located at 3,000 m above sea level at the foot of the Hindu Kush Mountains with a present earthquake threat. Considering traditional architecture and culture, this sustainability project was built with local materials, local knowledge, and created with local employment (AFIR-Architects, 2022). The centre was constructed on the top of a stone foundation with sun-dried brick walls and stone-decorated elevations (see Fig. 53). This complex building has a hall in the centre with administration and meeting rooms on one side and a sleeping room with kitchen and toilet on the other.



Figure 53: Band-e-Amir Visitor Centre plan and elevation (AFIR-Architects, 2022)

2. Maternity waiting homes was a project in collaboration with the Ministry of Public Health for Afghan hospitals (AFIR-Architects, 2011); UNICEF funded the projects and AFIR Architects (2011) coordinated it, managing to convince the Ministry to use local materials and traditions. Built with stone masonry foundations and sun-dried brick walls; the maternity waiting homes consist of a public reception space, private rooms with an inner garden for the women, and a buffer zone in between (see Fig. 54). Witnessing the success of this project, UNICEF decided to reproduce the project in Herat, Kandahar, Takhar, and Lagman (AFIR-Architects, 2011).



Figure 54: 3D view of maternity waiting home in Bamyan (AFIR-Architects, 2011)

3. Maria Garzia Cutuli Primary School was built in 2011 in Herat (Arch-Daily, 2022); this school represents an alternatively designed approach compared to the typical school designs that exist in Afghanistan. This primary school has a unique layout, such that inside the boundary wall, classrooms, teacher and administrative rooms are located at a distance around a library with double-height comparing to the other rooms (see Fig. 55). All the structures are built with reinforced concrete and infilled with fired brick. The buildings are painted with a blue colour to save the cost of the sand-cement plaster. The school thus provides a good example of modern vernacular architecture (Arch-Daily, 2022). A typical primary school has only one building, sometimes with separate administrative rooms. Furthermore, the size and location of the windows with different heights, especially for the library building, is a unique and new approach to a school project. While inside the vernacular school, there are elevations and windows with the same height as a common design approach. Another interesting point is the direct application of the paint on the brick walls without plaster.



Figure 55: Maria Garzia Cutuli Primary School in Herat province (Arch-Daily, 2022)

2.4.1 Receptivity to modern vernacular architecture

From construction to performance, buildings need energy, and this consumption increases everyday as more people gain access to housing; one of the ways to decrease this consumption is the use of local and sustainable materials. As for concrete

buildings, energy is required to produce raw materials and to cool and warm the building. Studies show that construction has a significant impact on energy use (Touré et al., 2017; Walker, 1995), and it is time to think wisely and use sustainable materials for construction. Recently, environmental impact and rapidly rising energy prices make it necessary to replace conventional concrete with a sustainable material, at least for residential homes. Building with earth could pose a real solution to this problem, if not working towards erasing the issue (Habert, 2016). Raw soil could thus potentially provide the answer to the problem of human construction needs, as it has been done so for thousands of years (Lucile et al., 2010). Its availability, recyclability, and embodied energy make it a unique construction material, (Reddy and Kumar, 2010). Raw soil is under our feet, thus locally available and in endless supply, traditionally used, and eco-friendly, and it would be difficult to find an equivalent sustainable material (Rijven, 2007). It also has a good thermal mass property, is economical, environmentally friendly, and without any transportation costs (Habert, 2016).

Nonetheless, soil does not have all the thermal properties it is claimed to have, but its volume, heat capacity, and time lag are unique. It pertains to non-renewable resource consumption, lacks waste, creates better indoor air quality, a disease-free environment by controlling humidity inside the rooms, and provides employment for workers (Pacheco-Torgal and Jalali, 2012). However, it has some disadvantages compared to conventional concrete, such as its durability, strength, being labour intensive, and in terms of construction in seismic areas (Pacheco-Torgal and Jalali, 2012). It is argued that for thousands of years, humans proved that they could live a sustainable and balanced life in harmony with nature, yet the twentieth century has disrupted this development (Auroville Earth Institute, 2020). Some researchers are looking to the twenty-first century to recreate this harmony between humans, nature, and sustainability (Auroville Earth Institute, 2020). The available codes and standards developed in different countries are mostly prepared for constructing roads. Therefore, there is a need to improve this weakness with new and specific codes for the housing sector

In addition to preserving nature, the earth construction has a great thermal buffering capacity (see Fig. 56) and provides a comfortable living environment to its residents. A study by Pacheco and Jalali (2012) shows that earth buildings control the indoor climate and maintain indoor humidity between 40 to 60 %, which humans require;

humidity below and above this causes some diseases. The diseases include itchiness, burning eyes, skin irritations, nausea, headaches, fatigue, reproductive impairment, impaired child development, and cancer. Buffering is the ability of the soil to absorb the humidity when it is surplus and release it when there is a lack of humidity.

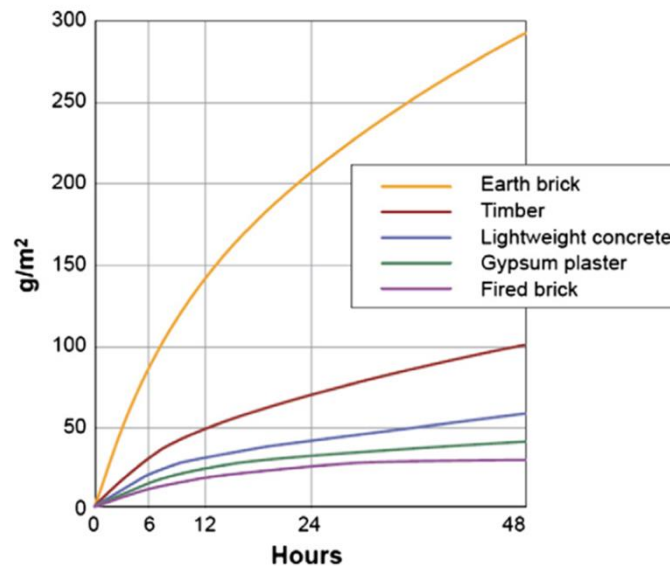


Figure 56: Weight of moisture absorbed when the humidity increases from 50 % to 80 % (Pacheco-Torgal and Jalali, 2012)

Considering all the benefits that vernacular architecture and local materials bring to the construction industry, it leaves practically a zero-carbon footprint. On the contrary, cement and concrete are the second most frequently used material on the planet after water, and their production accounts for 8 % of the greenhouse-gas emissions (Frey, 2010). For example, a lorry of cement loaded on a construction site requires 22,000 tons of carbon dioxide (Frey, 2010). Recyclability represents another issue with concrete, while local materials such as raw soil are entirely recyclable. Fortunately, recent environmental pollution came to the forefront in scientific research, and once again earth construction has caught the attention of various researchers (Jean-Claude and Walker, 2007). The aforementioned factors make this generation of architects and builders more receptive to modern vernacular architecture.

2.5. Why modern earthen architecture?

2.5.1. Social values

Raw soil one of the first construction materials, which has been used for over 10,000 years in the provision of human shelter (Pacheco-Torgal and Jalali, 2012), with 40 % of the world's population living in earth-made houses in 2020, and 17 % of the cultural

heritage sites worldwide are made with earth (Auroville Earth Institute, 2020). These cultural heritage sites have great social and historic value and need to be maintained. Moreover, 25 % of the UNESCO world heritage sites in danger are made with earth (UNESCO, 2021). There is an abundance of natural material free of charge, and a house made with earth is warm in winter and cold in summer compared to a fired-brick house (Heringer, 2020). Earth constructions, nonetheless, require a greater workforce and local resources compared to conventional constructions. To counter this, in low-income countries, the workforce is cheap, thus an earth construction is cheaper than a conventional one (Morel et al., 2001).

The research on building a primary school by German architect Anna Heringer is an excellent example. In 2005, this school building was completely made with earth and bamboo over four months by local craftsmen, pupils, parents, and teachers in Radrapur, a village in the northwest of Bangladesh. It has three classrooms on the ground floor and two on the first floor (see Fig. 57). The ground floor, with its thick walls, assures a comfortable climate, sunlight, and ventilation, regulated through the shutters (see also Fig. 57). Local building techniques were improved, and innovation was brought to the project; local people were employed as the workforce for the entire four-month project. The project budget was spent in the village and went into the pockets of the local people.

This approach could be applied in Afghanistan where the workforce is also cheap and in abundance. Thousands of Afghans are working with low wages outside the country in Iran and Pakistan as they cannot find employment in the country. New affordable houses built with CEB would help the local masons and artisans to establish local businesses and at the same time provide thousands of new responsive bioclimatic houses. This approach will not only create employment for Afghans, but it would retain a sense of history and tradition, bolster the local economy in the long term, and enhance social values. More importantly, earth houses are low-cost, and many Afghans can afford to build their houses by themselves.

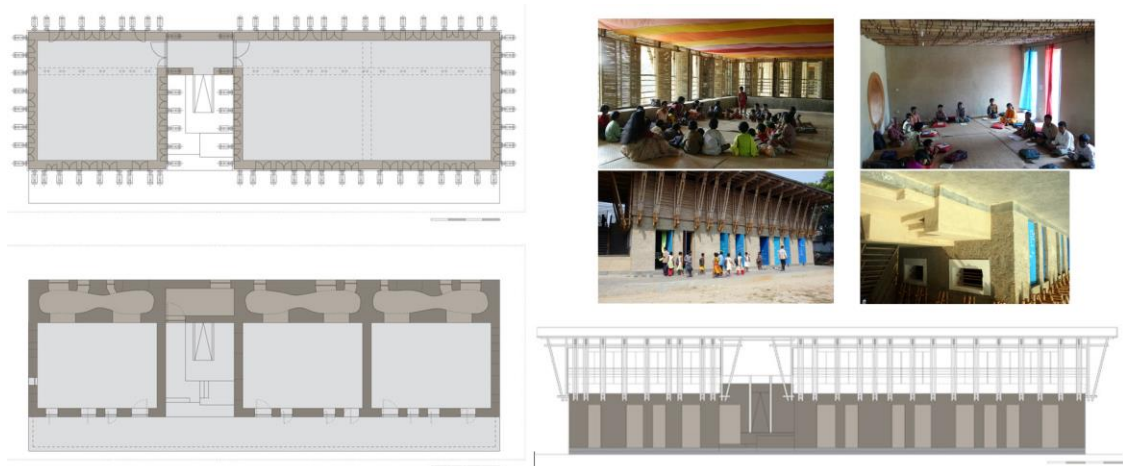


Figure 57: Modern school in Radrapur, Bangladesh (AKDN, 2007)

2.5.2. Energy demand

Building is responsible for consuming 40 % of the world's total energy, including embodied and operational costs (Minke, 2006; Habert, 2016; Mandley et al., 2015). Therefore, the building sector is responsible for producing a large percentage of the greenhouse gases, contributing directly to climate change. Soil has a good volume and heat capacity and is able to mitigate damp and provide thermal conduction by enabling external temperature flow into the interior (Houben and Guillard, 2014). In semi-arid climates such as Kabul, the walls of the mud houses act as a natural insulator, keeping them warm in winters and cool in summers. Earth-made houses with a high thermal mass are efficient in creating a comfortable indoor environment during both seasons. The traditional spatial planning for Afghan cities constitutes a passive design system in which the building plan relates to the trajectory of the sun, allowing for energy efficiency. In hot-arid climates as with northern Egypt with huge the differences in days and nights, the comfort of the people inside buildings largely depends upon the thermal properties of the walls and roofs (Frey, 2010). Historically, earth houses in Afghanistan have almost zero embodied energy, where unprocessed materials and cheap local workforces are used. Considering modern earth constructions with CEB, the only energy needed is for digging the site if the blocks can be prepared on a construction site with a manual handpress. However, this is not the case if the soil is stabilised with cement. However, the embodied energy of CSEB is 10.7 times less, and its carbon emission is 12.5 times less than fired bricks (Auroville Earth Institute, 2020). Thus, earth is a better composition to use for buildings.

2.5.3. Low-cost housing

In developing countries, the provision of adequate housing is a pressure and a challenge since most cannot achieve their hopes of having a private house. Those who can afford one are few and far between (Fathy, 1978). In some cases, once a house is built, it lasts for generations, from parent to child to grandchild. There are many examples of such housing in Kabul. As Sharifzai et al. (2016) has argued, in addition to being a necessity, shelter is a source of identity that affects human wellbeing and mentality. After food and clothing, shelter constitutes a basic human need (Sharifzai et al., 2016). Hence, it is necessary to adopt environmentally friendly local resources and cost-effective technology to enable low-income citizens to construct affordable housing.

The term low-cost housing does not mean sacrificing local ways of living, nor the performance of the building (Barot, 2021); it points to appropriate management of the budget, better use of local resources, skills, and modern technology to achieve cheap housing units. It also does not mean using cheap and low-quality materials; rather, low-cost is achieved through better management and using local resources that do not require costly maintenance. It means cutting the construction costs through the use of these local resources, skills, and alternative inputs to the conventional construction methods (Tam, 2011).

A good example of low-cost housing is the grid of an 8 x 8 m patio housing in Casablanca, Morocco, built by Michel Ecochard after the Second World War. This project was a rapid response to the urgent need for affordable homes and mass-housing construction in the country (Saaid and Chaoui, 2020). These small patio houses had two to three rooms, with a kitchen and toilet, enjoying maximum shared walls. A case study in India, where currently a shortage of 17.6 million houses exists, shows that the use of low-cost housing construction for walls and roofs can save 26.11 % and 22.68 %, of the total cost respectively, in comparison to conventional constructions (Tam, 2011). This is achieved primarily by using improved and innovative techniques. For wall constructions, rat traps bond technology is used as an alternative to English and Flemish brick bonding. This reduces the number of joints, with no plaster having to be applied to the walls, and this results in a lower consumption of mortar. A filler slab roofing system is applied, where less concrete is also required. Constructions with earth seem to provide a real solution to the problem of housing shortages. Oliver

(1987) states that 90 % of the housing shortage will be met by using vernacular architecture and using locally available resources and technology, rather than high-tech and specialised methods.

However, for low-cost housing, the choice of material and size of the building is limited to the locally available materials, such as soil, stone, and wood; for example, in Kabul, sun-dried brick and pakhsa are largely used for affordable homes. Over the last three decades, Afghanistan's urban population has increased rapidly, as previously mentioned (see Chapter 1). In addition, 49 % of migrants and internally displaced populations reside in urban areas, which in turn increases the housing demand for low-income people (MUDL, 2019). A great majority of these internally displaced urban populations and migrants live in the informal settlements. UN-Habitat (2020) states that 72 % of the urban population. In Kabul, people cannot afford conventional houses constructed under the current market conditions.

So it is quite logical to use the cheap-local material. Thus, there is a need for better management of the available resources and adopting modern methods and technology for the mass construction of this low-cost housing. For this, the use of earth elements studied in this research could be a suitable construction material that is affordable and environmentally friendly. Modern earth construction methods have many benefits compared to the traditional earth constructions, such as, durability, strength, quality, less construction time, and possibility of the prefabrication.

2.5.4. Productive settlements

In developing countries, most people do not have access to adequate housing, which relates to the relative poverty and income issues in these countries. One of the ways to promote sustainable communities is through productive settlements and a home-based economy. This can help the development of sustainable communities, which results in the promotion of urban developments. In vernacular settlements, compactness of form, efficiency of land use, and ecological and environmental advantages exist compared to dispersed forms of modern cities (Kazimee, 2008). Versus (2014) has defined the main features of productive settlements as proximity, collectivity, and integrated production, as further discussed in the next page:

Proximity: productive settlements usually have a well-defined boundary, which are often marked by a wall that is in-turn defined by a radius of a walkable distance. This considerably reduces transportation and infrastructure costs. Such communities have advantages on energy loss and consumption, increases in accessibility, and improvements to the local economy.

Collectiveness: people live as a community where they can share knowledge, deal with challenges, resolve problems together, and use the same infrastructure. Such interactions can occur in shared places such as factories, workshops, and laboratories where people can share their experience and knowledge with others.

Integrated production: in vernacular architecture, small-scale factories are located inside the community where production takes place. Therefore, the production is integrated into the daily life of the society.

In Kabul, there used to be many examples of productive settlements. The production of different musical equipment, pottery, kites, and daily household equipment were produced in the small communities, including in Shor Bazaar and Koch-e-Kharabaat. However, over the last two decades, with the coming of the US and coalition forces to Afghanistan, a great deal of money was pumped into the country; this resulted in replacing domestic products with imported ones, from neighbouring countries and China. However, the Murad Khani area in Kabul is a good example since it remains a productive settlement. An eighteenth century settlement was recently (in 2006) renovated and partly rebuilt by an international organisation, the Turquoise Mountain Foundation (TMF). This area of Kabul has many traditional hand-made jewellery and silver shops, ironsmiths, shops that prepare knives and axes for butchers, and shops that transform car and truck tyres into traditional flip-flops and equipment for carrying and keeping water. For daily social life, there used to be mosques, public baths, Takia Khana (places of worship), and the Abul Fazl pilgrimage, mostly visited by the community women (Woodbridge, 2012). However, currently, only the mosques and Abul Fazl remain, and the rest have either been destroyed or are unusable.

Recently, the US and coalition forces withdrew from Afghanistan, along with it their money and people; those who had worked with this republic government, that is the international companies and embassies, lost their jobs and businesses. This included more than 300,000 people who worked with the army, which included most civil-

service workers. In urban areas such as Kabul, this constitutes a catastrophe. One of the potential solutions to this crisis could be the revival of sustainable and productive settlements so that the families can earn their living through small-scale businesses within their communities.

2.6. Social housing in Afghanistan

There is a high demand for social housing in Afghanistan, which increases in urban areas. According to the housing policy, every year around 40,000 affordable homes need to be built, while only 5,000 are supplied annually (MUDL, 2019). This resulted in many living in informal settlements. It is difficult to find an example of social housing in Afghanistan, over the last twenty years, despite all the foreign aid and money coming into country. However, they were not able to build any social housing. There are three proposals for low-cost housing by the following department, institution, and scholar: 1. the Ministry of Urban Planning and Land; 2. UN-Habitat; and 3. Professor Bashir Ahmad Kazimee. However, none of them were able to be practically applied in Afghanistan. The three models proposed are discussed in further detail in Chapter 5.

2.7. Methodology

The research will be conducted in four main steps: first, the soils of different areas within Kabul will be selected and characterised according to the soil mechanics. Then various earthen elements such as sun-dried brick, CEB, and CSEB will be made and analysed. From those elements, the one with the highest compressive strength will be selected, and a model house with various wall thicknesses will be designed. Software simulation will make it possible to choose the optimum wall thickness and energy demands of the model house. After analysing the cost, a complete model for affordable housing construction for Kabul city will be proposed (see Fig. 58).

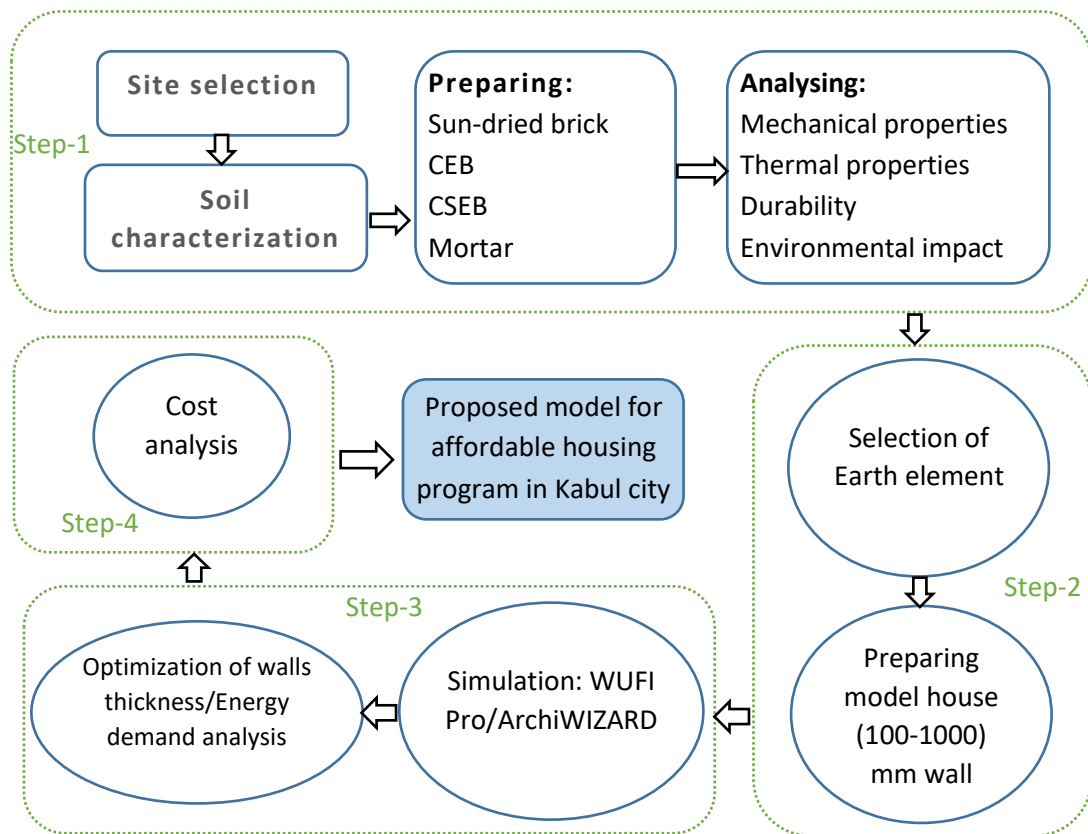


Figure 58: Research methodology

2.8. Conclusion

This chapter has provided a look at the history and techniques of building with earth. The most frequently used techniques, such as CEB, RE, sun-dried brick, pakhsa, and wood structures with brick infill, have also been detailed. Traditional earth architecture and receptivity to modern earth architecture have also been discussed. The common vernacular housing form, social value, energy demand, roof shapes, and natural ventilation systems have been described, providing recommendations for affordable housing. It has also discussed the thesis methodology and steps for undertaking this research project.

In the subsequent chapter, the necessary experiments are analysed. For this, in Kabul, sample soils were collected, and their texture distribution, hydraulic properties, suitability for construction, Proctor and shrinkage tests were performed and are reported on in the next chapter.

CHAPTER 3
PHYSICAL PROPERTIES OF THE
SOIL

CHAPTER 3: PHYSICAL PROPERTIES OF THE SOIL

The objective of this chapter is to determine the physical properties of the soil used from different locations within Kabul. To understand its suitability for preparing the earthen elements, it is important to know the physical characteristics of this soil because not every type is necessarily suitable for construction. Therefore, in this chapter, soil location, texture, hydraulic properties, Atterberg limits, suitability for earth construction, standard Proctor tests, and linear shrinkage limits tests are examined in relation to the three soil types. This will help to select the appropriate soil for this study.

3.1 Soil locations

In Kabul, there are many places where soil for construction purposes exists. For this study, three sites located in Kabul were selected for study in this thesis (see Fig. 59):

- Deh-Sabz district to the north of Kabul;
- Arghandi in Paghman district, west of Kabul; and
- Band-e-Ghazi in Surobi district, east of Kabul.

In Kabul, mainly three types of soils exist that are mostly used for construction, including yellowish (Deh-Sabz), whitish (Arghandi), and reddish (Band-e-Ghazi) soil, as shown in Figure 59. Currently, in Kabul, the majority of fired bricks come from Deh-Sabz and Arghandi, and it is believed that these districts have a good quality soil for producing baked bricks. Many small companies exist in which fired bricks are traditionally made from sun-dried bricks. Band-e-Ghazi's sandy soil is mostly used for roads and pedestrian-route constructions.



Figure 59: Three soils location in Kabul (University of Texas Library, 2020)

3.2 Methodology of soil characterisation

Thus far, there has not been a standard code of practice available to analyse the raw soil and earth elements for construction; therefore, in addition to the available European standards, this thesis also employs the American Society for Testing and Material (ASTM) standard building codes. In this section, all the methods used to analyse the three soils are summarised in detail.

1. **X-ray diffraction** was performed on a Bruker Advance D8 diffractometer in a θ - θ configuration using $\text{CuK}\alpha$ radiation ($\lambda = 1.54 \text{ \AA}$) for Deh-Sabz, Arghandi, and Band-e-Ghazi soils. The diffractogram was recorded between 2° and 55° with the Lynxeye detector, as shown in Figure 60. The duration of the recording was 3 hours. The qualitative analysis was carried out with the software X'Pert HighScore plus 2.2.
2. **Sieve analyses** were conducted to find the particle size distribution of the soil; first, the dry sieve analyses were performed in line with the ASTM (2001). One kilogram of oven-dried soil was sieved through a set of sieves (shaken well for 8 minutes in an automatic shaker) to access to the quantity of clay (particles less than $2\mu\text{m}$ in diameter), silt (between $2 \mu\text{m}$ and $75 \mu\text{m}$), sand (between $75 \mu\text{m}$ and 2 mm), and a fraction of gravel (more than 2 mm). With the dry sieve analyses, it was not possible to find out the exact particle-size distribution; hence, the wet sieve analyses were conducted. First, one kilogram of oven-dried soil was washed in a $75 \mu\text{m}$ sieve. The passing fraction of this first step enabled access to the quantity of clay and silt.
3. **Natural moisture** content was determined and conducted according to the ASTM (2019) standard test for a laboratory determination of the water content in the soil and rock by mass. The testing procedure includes weighting an empty can (W_1), adding natural soil into it, reweighting the can with the natural soil (W_2), and leaving the can with soil in the oven ($110^\circ\text{C} \pm 5^\circ\text{C}$) for 18-24 hours. Then, the can was removed from the oven and left in an open space to cool and was reweighted to find the weight of the can including the oven-dried soil (W_3). Finally, the moisture content was calculated following this formula: $(W_2 - W_3)/(W_3 - W_1) * 100$.
4. **The Atterberg limit** tests have been conducted on the soil sample passing a $425 \mu\text{m}$ test sieve, following the ASTM-D4318 specifications (Trujillo and

Trujillo, 2016). The soil remains in water for 48-72 hours and is then pressed through a sieve of 425 μm . From this mixture, 50-70 gr in a pasty consistency was placed in a bowl of casagrande, and its surface smoothed and grooved at a maximum of a 10-mm height. By turning the handle at a speed of 2 cycles/sec, the bowl was dropped until the groove closed at a 10-mm length. When the groove closed at 25 strokes, 5 cm^3 , it was taken from the centre of the bowl, and the water content of the mixture was found to be equal to the liquid limits. The same mixture was used for the plastic limit, rolled by hand onto a water absorbent surface into small threads of 3 mm in diameter. Then, the threads were moulded into a ball and rolled again. This procedure was repeated until the threads began to crumble at a 3-mm diameter. 5-7 gr of this mixture were immediately weighed and then oven dried to obtain the water content. This test was repeated three times, and the average defined the plasticity limits for the three soils

5. **Standard Proctor test** was performed on all the soil following the ASTM-D-698 (ASTM, 2014). To do the test, 12.5 kg of dry soil was mixed with 6 % of water by weight for Band-e-Ghazi sandy soil and 8 % by mass for the other two clayed soils; they were mixed by hand and left in a covered plastic container for 24 hours. Then, the soil was divided into 5 parts: the first portion was immediately added to the mould in the three layers and was compacted with a 5.5 lb hammer dropped at 25 falls per layer; for the second portion, 2 % more water was added; and for the third, fourth, and fifth portions, (4, 6, and 8) % more water was added and compacted, the same as the first portion.
6. **Linear shrinkage test** was conducted according to a German standard: DIN 18952, (DIN 18952, 1956), which required that the soil had a comparable plasticity. This standard adhered to the following steps to obtain a standard stiffness, and the shrinkage limit test should be performed on a soil with a certain stiffness. The soil had to be sieved in a 2-mm sieve to remove any particles larger than 2 mm. 1,200 cm^3 of this soil had a slight moisture and was hammered on a flat surface to produce a continuous piece. These pieces were then converted into 2 cm wide strips and placed edge to edge, touching each other and hammered again. This process is repeated until all the material showed an even structure. In order to equally distribute the water into all the materials, loam with less clay content must rest for 6 hours, and loam with

more clay content must rest for 12 hours. From these loams, 200 g is cut, and a sphere ball is made from it and dropped from a 2-m height onto a flat surface; when the diameter of the flattened surface thus formed 50 mm, a standard stiffness was reached. A few balls were dropped, and the difference between the smallest and largest diameter should not be more than 2 mm. If it formed a diameter smaller than 50 mm, a few drops of water could be added; however, if it was larger than 50 mm, then the loam could be dried slightly, and the same procedure was performed until the exact stiffness was achieved. With this standard stiffness, shrinkage limits tests were performed as follows: the mixture was pressed by a timber hammer into a framework sized (25 x 25 x 220) mm and rested on a flat surface (see Fig. 70). At least three samples had to be prepared, and their length after casting needed to be cut into 200 mm. All the samples must be air-dried for three days and then oven dried (60 °C) until no more shrinkage was able to be measured. The average of the linear shrinkage of the three samples (200 mm) gave the linear shrinkage of the mixture. However, if one of the three samples had a difference of more than 2mm, compared to the other two samples, the procedure needed to be repeated.

3.3 Soil texture

3.3.1 XRD analysis

For Deh-Sabz and Arghandi soil, the diffractograms mainly present calcite and quartz; a separation of a sample of less than 2 μm was carried out to highlight the clay part. The samples were mainly composed of limestone and quartz, and the presence of chlorite and muscovite was also clearly observed (see Fig. 60). Moreover, the presence of chlorite in the sample was confirmed by the heating treatment. The petrography of the two soils was quite similar. However, Band-e-Ghazi soil mainly contained quartz and calcite, and the presence of chlorite and muscovite were not as visible as in the Deh-Sabz and Arghandi soil.

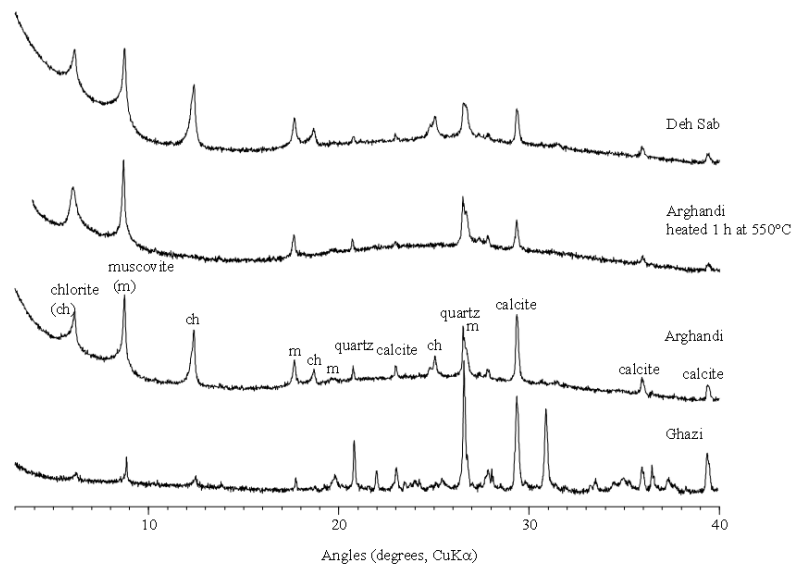


Figure 60: X-ray diffraction analysis result

3.3.2. Specific density

To find out the specific density of the soil, a true density analysis was performed on a Helium pycnometer machine. By dividing the real mass of the soil by its weight, the following results were obtained:

- Deh-Sabz: 2.74 gcm⁻³ (measured average value: 2,7398 gcm⁻³)
- Arghandi: 2.74 gcm⁻³ (measured average value: 2,7432 gcm⁻³)
- Band-e-Ghazi: 2,8 gcm⁻³ (measured average value: 2,7787 gcm⁻³)

3.3.3 Sieve analysis

3.3.3.1 Dry sieve analysis

As can be observed in Figure 61, the clay and silt content is 6.82; 9.75, and 9.33 % for Deh-Sabz, Arghandi, and Band-e-Ghazi soils, respectively. The percentage of sand is 55.65; 50.46; and 37.8 %, respectively, and the gravel content is 37.53; 39.79; and 52.82 %, respectively. This result shows that the clay and silt content are low (less than 10 %) in all the three soils, while the sand and gravel content is very high. It was also found that in Deh-Sabz and Arghandi soil, many small- and big-sized clods exists, while in Band-e-Ghazi soil only small-sized clods were found. During this experiment, those clods were classified as sand and gravel (see Fig. 62). The clods were mixed in with sand and gravel particles, so it was difficult to distinguish between the real sand and gravel and the clods (see Fig 63). Therefore, to find the exact texture distribution of the three soils, a wet sieve analysis was performed.

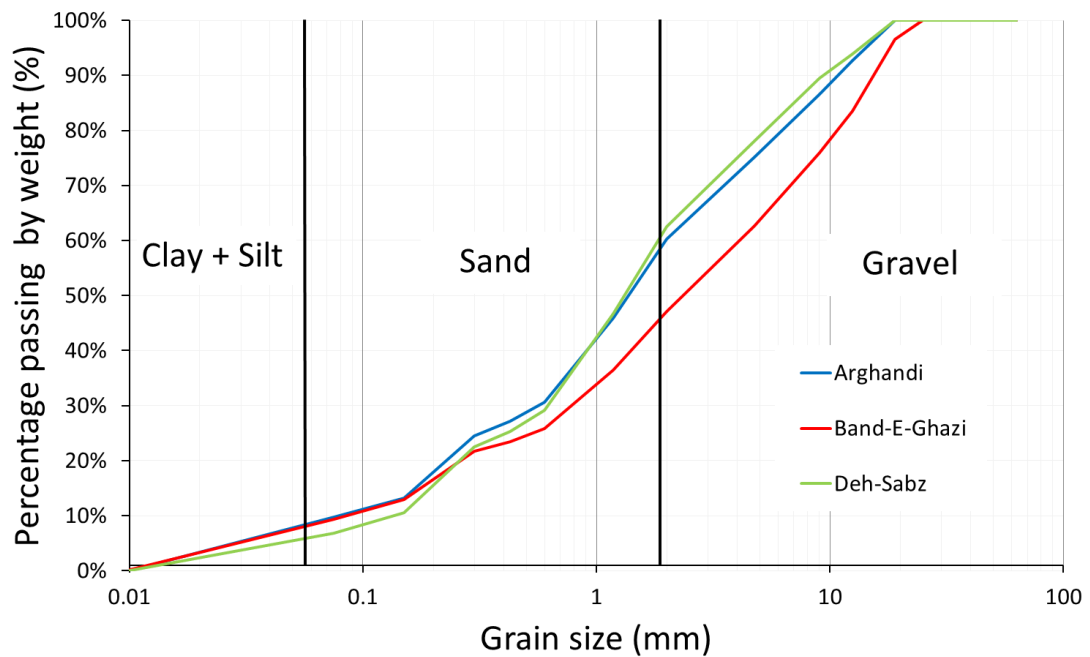


Figure 61: Dry sieve analysis result



Figure 62: From left to right: dry sieve analysis from Deh-Sabz and Band-e-Ghazi and an automatic shaker (photographs by the author)

3.3.3.2 Wet sieve analysis

The results of the wet sieve analysis show that the clay and silt content is extremely high for Deh-Sabz and Arghandi soil, 98.0 % and 93.7 %, respectively (see Fig. 63). For Band-e-Ghazi soil, this percentage is only 31.2 % (see also Fig. 63). Then, the rejected fraction in the 75 μm sieve was oven dried and sieved through a set of sieves to find the fraction of sand and gravel. The results of this second step show that the sand content was extremely low for Deh-Sabz and Arghandi soil, 1.8 % and 5.18 %, respectively (see also Fig. 63). For Band-e-Ghazi soil, this percentage was 29.7 % (see also Fig. 63). The gravel content was also extremely low for Deh-Sabz and Arghandi soil, 1.2 % and 1.4 %, respectively (see also Fig. 63), while for Band-e-Ghazi soil, the

gravel content was extremely high, with a percentage of 39.1 % and a maximum particle diameter of 19 mm. Finally, Band-e-Ghazi soil appears to be well-graded, but Deh-Sabz and Arghandi soil are uniformly graded as fine-grained.

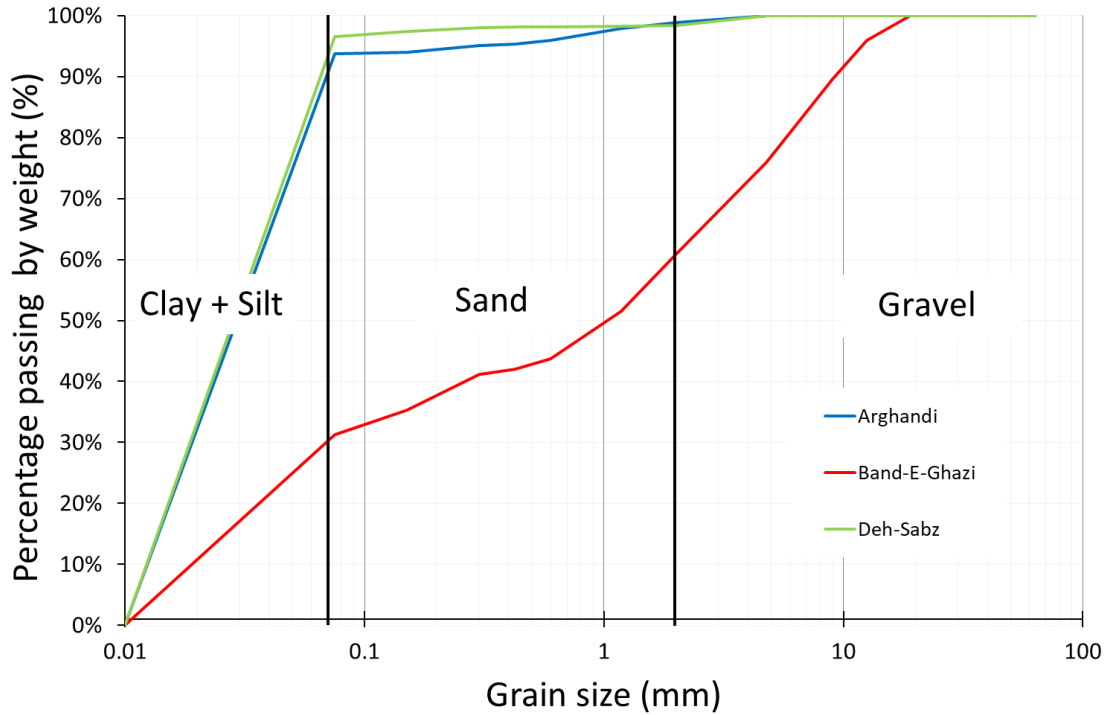


Figure 63: From top to bottom: wet sieve analysis result and remaining sand and gravel after washing Deh-Sabz soil

3.4 Hydraulic property

3.4.1 Natural moisture content

The natural moisture content gives an idea about state of the soil in the field. It is the ratio of the weight of water to the weight of solids in a given mass of soil, usually this ratio is expressed in a percentage. The results showed that Band-e-Ghazi soil had the lowest natural water content (0.854 %), which might be due to an increased sand content in this soil. However, Deh-Sabz soil had the highest natural water content (4.7 %), and Arghandi (1.95 %) was between the two (see Fig. 64). The results demonstrate that the finer the grain that exists in the soil (Deh-Sabz), the more moisture the soil has; however, the more sand and gravel in the soil (Band-e-Ghazi) results in having less natural water content.

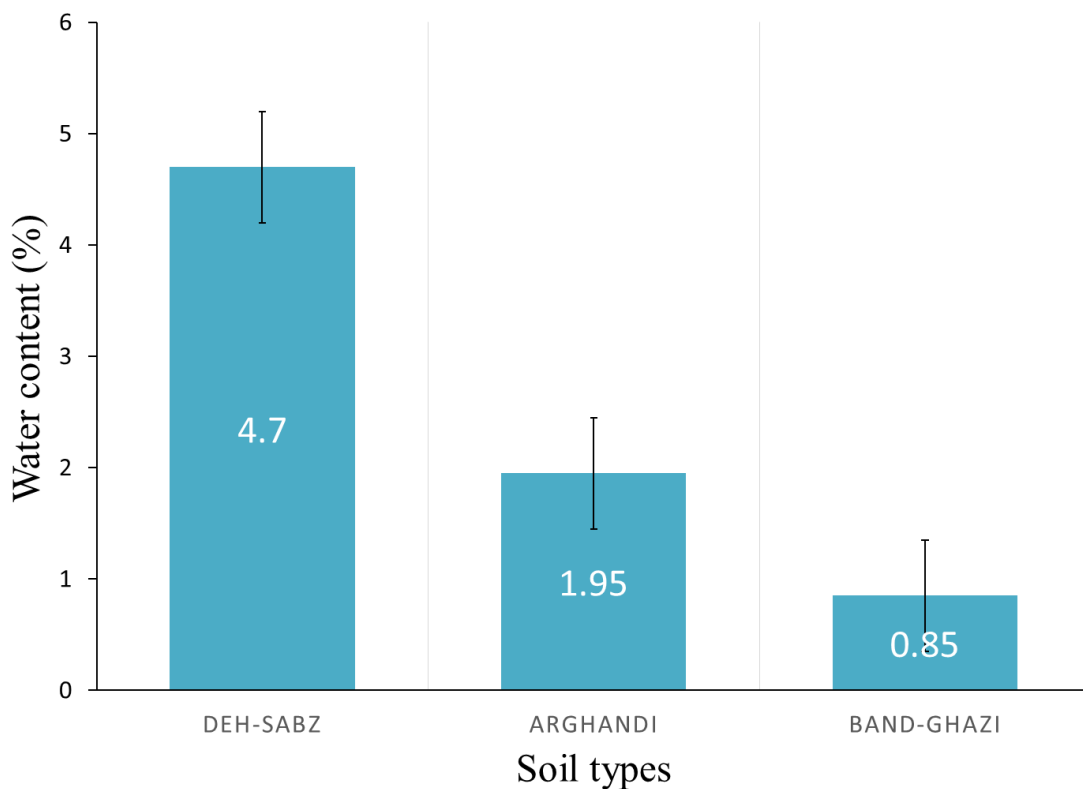


Figure 64: Natural moisture content for the three soil types

3.4.2 Atterberg limits

The Atterberg limits, determined by the scientist Atterberg, can be used to distinguish between silt and clay and between the different types of silt and clay. The water content at which the soil changes from one state into another is known as consistency limits or Atterberg's limit. The critical water content of a fine-grained soil are its

plastic limit and liquid limit. Loam has four different consistency states: solid, semi-solid, plastic, and liquid (see Fig. 65), which are described in further depth below.

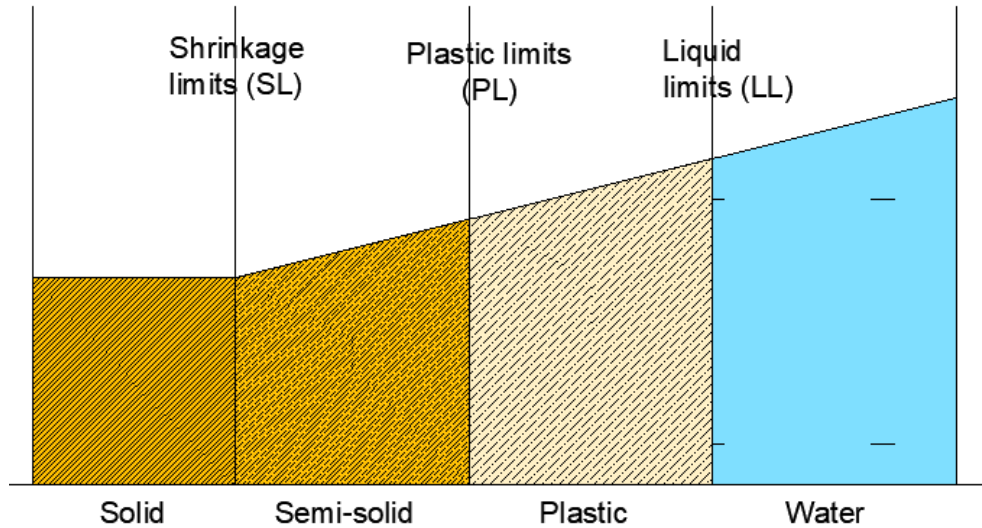


Figure 65: Four different consistency states of the soil

1. Liquid limits (LL): There is a defined procedure to conduct the liquid limit test; based on this procedure, tests were performed on the three soil types, and the results are shown in Figure 66.
2. Plasticity limits (PL): These limits constitute the boundary that exists between the state of being liquid and semi-solid. The results of the test indicate that the three soil types have similar plasticity limits (see Fig. 67)
3. Plasticity index (PI): The state between being plastic and semi-solid refers to the plasticity index, which is equal to $PI = LL - PL$ (see also Fig. 67). With the plasticity index between 7.2 and 15.3, all three soil types may be qualified as slightly plastic. For Deh-Sabz and Arghandi soil, the liquid limit was qualified as medium. For Band-e-Ghazi soil, the liquid limit was qualified as weak. The liquid limits of 50 % and above are considered high.

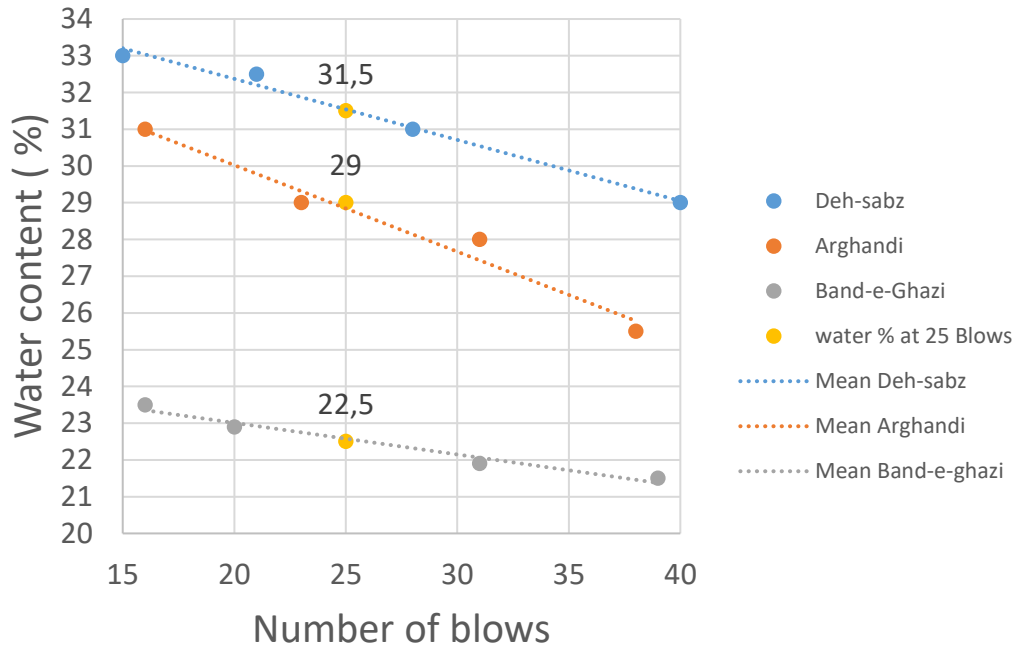


Figure 66: Liquid limits result

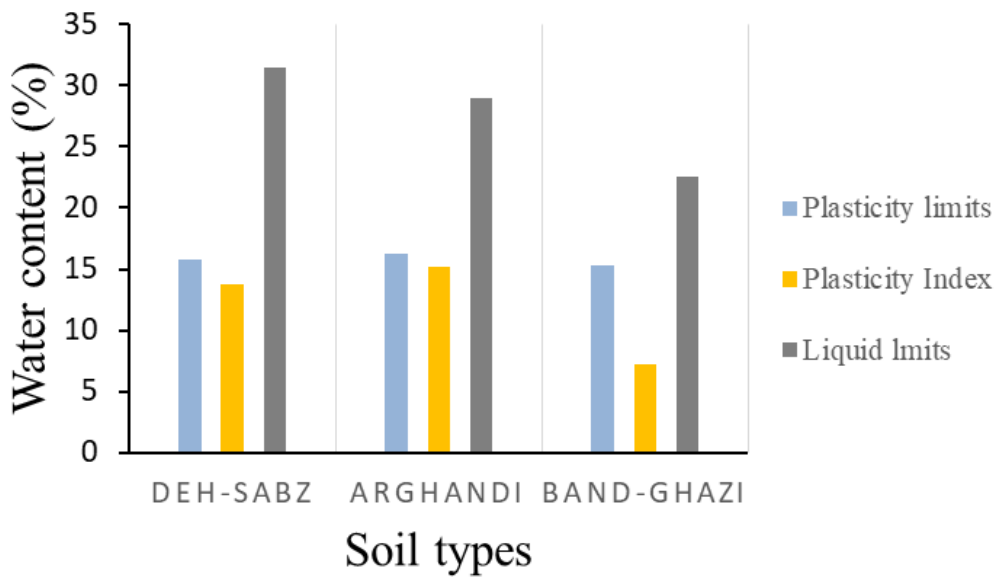


Figure 67: Atterberg limits result

3.5 Soil suitability for construction

AFNOR XP P13-901 (2001) and MOPT (2012) are standard codes that have developed a boundary polygon based on soil liquid and plasticity limits to find out whether a soil is suitable for earth construction (see Fig. 68). Based on these definitions, the test results indicate that Deh-Sabz and Arghandi soil are suitable for earth construction, while Band-e-Ghazi is close but falls just outside of the polygon boundary. This is due to the weak liquid limit of Band-e-Ghazi soil. However, this

result does not exclude this soil because as Accetta (2003) has shown, any soil outside the polygon might be also good for earth construction, such as with Lattes soil used by the Romans to build their house in the Lattara archaeological site. Furthermore, good soil for stabilisation should have the following specifications: 20 to 35 % clay, between 70 and 85 % sand, with a $LL \leq 30 \%$, and the $PI \leq 15 \%$ (Walker, 1995). Similarly, Bryan (1988) indicated that the clay content should be 5 to 30 %, sand content 35 to 80 %, and $LL \leq 40 \%$.

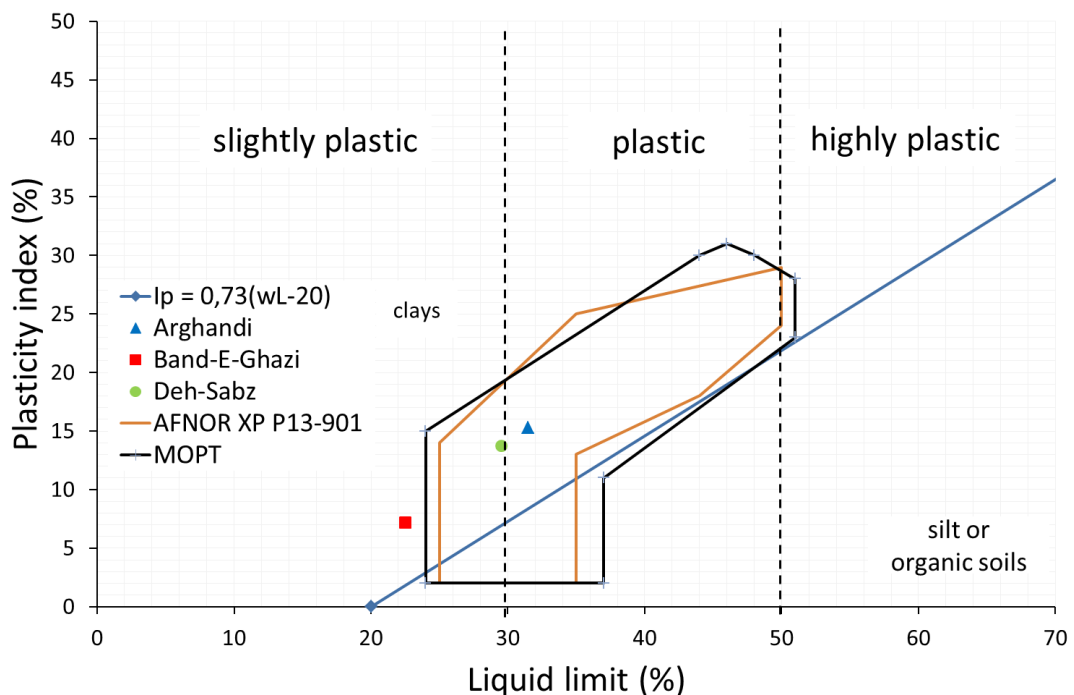


Figure 68: Soil suitability based on LL versus PI (AFNOR - XP P13-901, 2001; MOPT, 1992)

3.6 Standard Proctor test

For the CEB, the laboratory compacting procedure was used to find the relation between optimum moisture content (OMC) and maximum dry density. The results (see Fig. 69) show that all soil types are below the saturation line at 80 % humidity, except for Deh-Sabz. Moreover, Band-e-Ghazi soil has the maximum dry density and minimum water content (8 %), while the other two soils have a similar dry density, but with a wide variation in OMC (Arghandi 13 % and Deh-Sabz 17 %). Moreover, this test showed a relation between water content and soil grain size distribution: the finer the particle (clay and silt), the greater the water required, and the less dry density achieved. However, the lower the amount of clay and silt contained in the soil, the less

water required, and the better dry density achieved. The dashed blue and green lines present the Proctor test results for the reconstituted Arghandi and Deh-Sabz soil. The reasons and percentages for the sand for the reconstituted soil is defined in Chapter 4. The OMC for these are 11.57 and 12.25 %, respectively. The graph indicates that Deh-Sabz and Arghandi soil have increased fine particles and the lowest dry density while Band-e-Ghazi has fewer fine particles and the highest dry density (see Fig. 69). The water content for the CEB and CSEB mixtures were selected based on the Proctor test results.

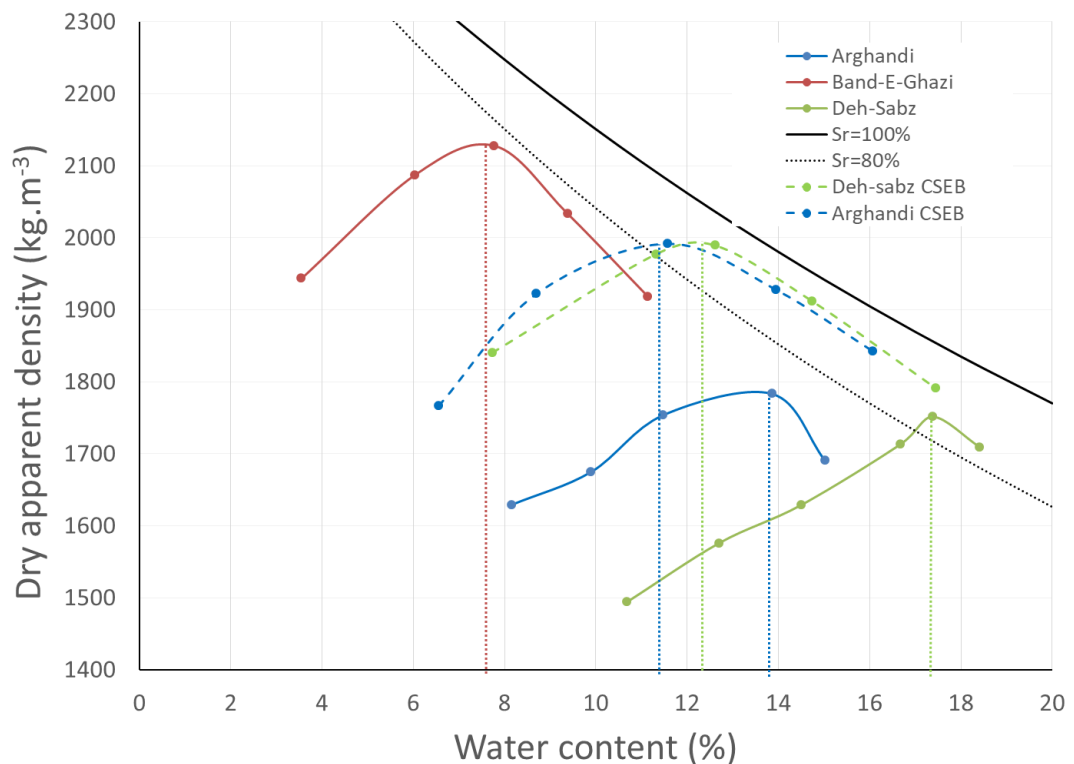


Figure 69: Standard Proctor test experimental procedure

3.7 Linear shrinkage limits (LS)

The linear shrinkage test procedure performed on the three area soil types (Deh-Sabz, Arghandi, and Band-e-Ghazi) and their average shrinkage limits are shown in Figure 70. A study on the soil suitability for compaction shows that soil with LS < 6 is good, and soil with LS 6 to 11 is acceptable. Nonetheless, soil with LS > 11 is not favourable for compaction (Burroughs, 2008). Fortunately, the linear shrinkage results of the three soil types are in the range of good soil in line with the Burroughs' (2008) classification.

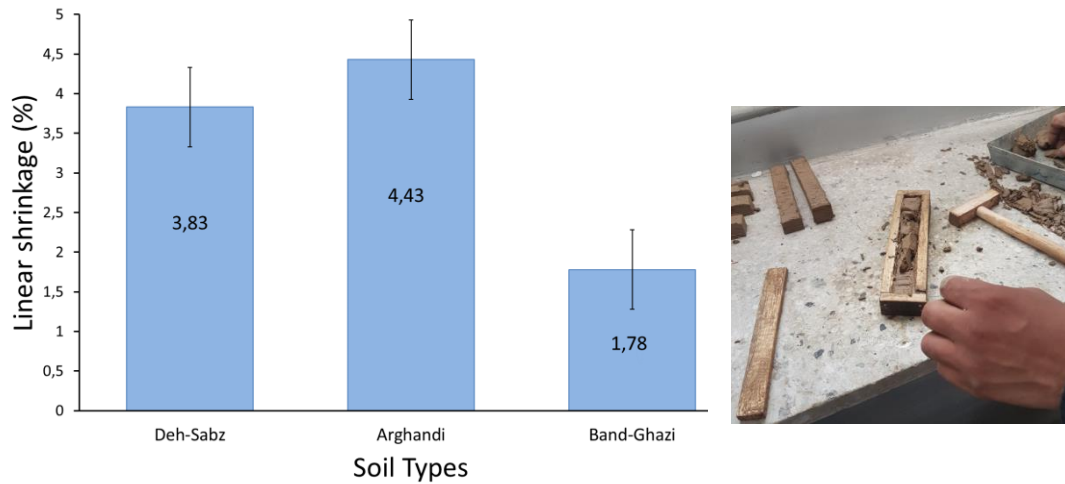


Figure 70: From top to bottom: experimental procedure and linear shrinkage results (photograph by the author)

3.8 Conclusion

Analysing the physical properties of the three soils constituted the necessary steps to knowing their main characteristics and suitability for construction. The presence of quartz and calcite has been observed in all soil types; however, chloride and muscovite were relatively lower in Band-e-Ghazi. The sieve analysis has showed that the clay and silt content was extremely high in Deh-Sabz and Arghandi (98 % and 93.7 %), while for Band-e-Ghazi, it has been concluded to be a well-graded soil with a high gravel percentage (39.1 %). Band-e-Ghazi had weak liquid limits, and the other two soils qualified as medium. Deh-Sabz and Arghandi soils were inside the boundary polygon, which indicated that they are suitable soil types for construction. Band-e-Ghazi had the maximum dry density and minimum water content while the other two soils had similar dry density levels, with a large variation in water content; all the three soil types had less than 6 % shrinkage limits, which has indicated that they all qualify for the category of good soil for compaction.

It has been found that the three studied soil types are suitable for earth construction. However, the compressive strength of the earthen elements has enabled the determination of one soil as having the higher compressive strength. Understanding the physical characteristics of the three soil types has made it possible to prepare the earth elements and analyse their mechanical properties, thermal properties, and durability in the next chapter.

CHAPTER 4
EARTH ELEMENTS

CHAPTER 4: EARTH ELEMENTS

In previous chapter, the physical properties of the three soil types were discussed. In this chapter, three different sample elements including sun-dried brick, compressed earth block (CEB), and compressed stabilised earth block (CESB) will be made from each soil type. The objective is to find a good mixture proportion by analysing their mechanical, thermal, and durability properties. This will lead to the selection of the most appropriate and fitting earthen element for the proposed low-cost housing construction programme in Kabul. Further, the mixture proportion (of soil, sand, and water), crack, and cohesion tests will be conducted on the selected element's soil, thus determining the best mortar proportions for the construction of the walls. Finally, from the mortar and selected earth element, two wallets (slenderness 1 and 2) will be made to find the loads that they are able to tolerate.

It should be noted that this is not a material-engineering thesis, rather an architectural one, which endeavours to find a solution to the problem of affordable housing in Kabul. The main objective of Chapters Three and Four is to select the best raw soil and earth element because there is a lack of research on the characteristics of soil in Kabul.

4.1 Mixture proportion and production

4.1.1 Mixture design

For the sun-dried brick, the water content was determined by the liquid and plasticity limits (see Tab. 2). The water content for Deh-Sabz and Arghandi sun-dried brick was similar; this might be due to their similarities in liquid limits (31.5 % and 29 %) and grain size. However, it was not the case for Band-e-Ghazi soil because it had lower liquid limits (22. %) and a different texture that required less water. This was confirmed by the wet sieve analysis in Chapter 3, where the amount of soil particles passing through a sieve of 425 micron was 98 %, 95 %, and 42 % for Deh-Sabz, Arghandi, and Band-e-Ghazi soil, respectively. The amount of clay and silt was less in Band-e-Ghazi soil compared to the other two soil types. The raw soil was left in water for 24 hours, and then the bricks were produced using a hand-made mould. Because small particles caused clods, for the CEB, the soil was first sieved through a 10-mm mesh and its water content was determined as being on the dry side of the OMC, as shown by the Proctor test (see also Tab. 2). For the manufacturing of the CSEB, Burroughs (2008) argues that good soil for cement stabilisation should contain between 21 % and 35 % of silt and clay. The Band-e-Ghazi silt and clay content was in

this range. For Deh-Sabz and Arghandi soil, it was not the case. Therefore, a reconstituted mixture has been prepared with 75 % of river sand (less than 2 mm) and 25 % of soil (see also Tab. 2). The cement content represented 10 % of the dry granular mixture for Deh-Sabz and Arghandi soil types and 9 % for Band-e-Ghazi soil (see also Tab. 2). The water was added by the degree, while the mixing continued, until a cohesive mixture on the OMC was achieved.

	CSEB				SDB			CEB		
	AR	BG	DZ		AR	BG	DZ	AR	BG	DZ
Silt/clay	444		442							
Sand (kg)	1333	1763	1328	Soil (Kg)	1697	1922	1595	1834	1966	1861
Cement (kg)	198	196	197	Cement (kg)	0	0	0	0	0	0
Water (kg)	247	168	246	Water (kg)	441	317	524	238	157	298
Water content (%)	12.5	8.6	12.5	Water content (%)	26.0	16.5	29.0	13.0	8.0	16.0
Volume (kg/m ³)	2222	2127	2213	Volume (kg/m ³)	2138	2239	2151	2072	2124	2158

Table 2: Mixture proportion for sun-dried brick, CEB, and CSEB

Note 1. AR (Arghandi), DS (Deh-Sabz), and BG (Band-e-Ghazi)

Note 2. SDB (Sun-dried brick), CEB (Compressed Earth Block), and CSEB (Compressed Stabilised Earth Block)

4.1.2 Production

The sun-dried bricks were made using a traditional handmade mould measuring (200 x 100 x 100) mm (see Fig. 71). 24 hours after demoulding, the bricks were placed in a dry place (top-down) to dry. For the CEB and CSEB, the wet mixture was then compacted into blocks measuring (290 x 145 x 100) mm using a manual hand-operated constant volume block machine (see also Fig. 71). The study was limited to a manual block press, as these machines are most widely used. Under normal operations, the single acting ram develops compaction pressures between (2 and 4) MPa. After compaction, the blocks were immediately extracted from the mould and carefully stacked for curing. The CEBs were air dried in the laboratory before tests. However, the CSEBs were moist cured for three weeks (see Fig. 72). During the first week, water was sprayed on the blocks on a daily basis. During the two following weeks, they were stacked under plastic sheets to maintain the required humidity for cement hydration

(Walker, 2004). Finally, in the fourth week, they were air dried in the laboratory before testing.



Figure 71: From left to centre/right: production of the sun-dried brick and CSEB



Figure 72: From left to right: initial and final curing of the sun-dried brick, CEB, and CSEB

4.2 Methodology

This study aimed to maximise the use of European codes norms, but they were found to be lacking, so they were supplemented by the ASTM (2002). The methods to conduct the experiments on the earthen elements and mortar are below. The methodology is summarised in here, and the results are discussed afterwards.

1. **Mechanical properties (flexural and compressive):** *For the 3-point bending strength*, the testing procedure applied adhered to the ASTM-c78 specifications. All the earth elements were tested at 7 and 28 days. The specimens were tested using a 50 kN mini-flexural 3-point manual hand-operated machine. Two supports were placed under the block inset from either end, thus creating a simply supported condition. A gradually increasing load was applied to the midspan of the block until failure occurred. Failure is expected to occur due to tension in the bottom face of the brick, and since its location was a function of the support (see Fig. 73). A 25-mm distance between the bottom face support and the block corners was observed (ASTM, 2002), leaving a 250-mm span between the two supports (see also Fig. 73). *For the compressive strength*, the testing procedure was developed for fired brick in

accordance with the British Standard Institute (1985). All the elements were tested at 7 and 28 days. Before testing, the samples were weighted and measured to calculate the apparent dry density. They were capped on both sides (see Fig. 76), with 3-mm thin sheets of plywood for a better distribution of load (Walker, 2004). The specimens were tested using a semi-automatic ADR-2000 BS concrete cube-testing machine with a loading speed around 2 MPa/min until failure.

2. **Durability test:** Two types of test were conducted (a= water absorption and b= erosion test):

a. For the water absorption test, three series of tests were performed on various elements: 1) water absorption was performed by a capillarity test, based on a modified methodology by Varum et al. (2007), conducted on CEB. For each treatment, five specimens were cut in half after drying. The previously weighed samples were placed in a metal box of (65 × 40 × 13) cm and filled with water (17) litres until the samples were completely submerged (see Fig. 79). The samples had to be reweighted after 6 hours to obtain the amount of water absorbed. The soil deposited in the boxes needed to be oven dried and weighted to calculate the mass loss. In addition to the using an adapted version of Varum et al.'s (2007) methodological procedure, the testing procedure was further developed for CEB walls and partitions, (AFNOR - XP P13-901, 2001), and the French standards were followed for the CEBs. The block was submerged 5 mm face down in water for 10 and 60 minutes, and the water was absorbed during that time.

2) For the CSEB water absorption, the testing procedure developed for fired bricks by ASTM (2015) was followed. However, the CSEBs were not boiled in water, as the code requires for fired brick. The specimens were submerged in water for 24 hours to find the percentage of water absorbed during that period.

3) Moreover, for the sun-dried brick and CEB, the testing procedure for the determination of the water absorption by using a capillarity test with the code, EN 15801:2009 was followed. This testing method can be applied to porous inorganic materials, untreated ones, or those subject to any treatment or ageing. Consequently, three sun-dried bricks and three

CEB specimens were placed inside two separate plastic boxes with a bedding layer of absorbent cotton on the bottom (see Fig. 81). Water was added until saturation of the cotton was achieved, and the specimens were then placed on top of the cotton. The specimens were remain for 24 hours on top of the cotton. The percentage of water absorption by the capillarity test and height of the capillary rises were measured after 24 hours.

- b. An abrasion test was also carried out according to the standard testing procedure developed for earth blocks (AFNOR - XP P13-901, 2001). The objective of the test is to subject the block to a friction executed by using a 25 mm \pm 2 width steel-wire brush loaded with a 3-kg weight. The brush moved forwards and backwards on the outer face of the block, one round trip per second for a minute or a 60-second round trip. Brushing needed to be done along the entire length of the block, and at least half of the brush surface had to remain in permanent contact with the surface of the block throughout the test. This was to avoid putting more strain on the edges of the block. At the end of the brushing, the block was cleaned of the material that had come loose and reweighted to find the loose material caused by the abrasion.
3. **Thermal property of the elements:** This was measured by the ISOMET Model 2104 heat transfer analyser. It is a portable measuring instrument with surface and needle probes for obtaining a direct measurement of the thermo-physical properties of a wide range of isotropic materials. The surface probe needs a minimum of a 60-mm diameter flat surface, and the minimum thickness requirement is 10 to 15 mm.
4. **Mortar:** For the mortar, a mixture proportion analysis and mechanical strength tests were conducted.
 - a. Mixture proportion: a matrix of 9 mixtures with various soil, sand, and water ratios was prepared, in accordance to the guide to good practice on earth construction and earth coating (Savira and Suharsono, 2020) for Deh-Sabz soil (see Tab. 7). The purpose of this experiment was to find out the ratio for a good design mix that can be used for the mortar and interior plaster. Soil and sand were sieved through the ASTM sieve No. 10 (2 mm). The nine different mixtures were made in a wooden framework (25 x 25 x 1 cm) and left for 28 days to dry (see Fig. 87).

- b. For the flexural and compressive strength, the European Standard (BS EN 196-1: 2016) was applied, and a testing procedure was developed for the determination of the cement strength. For the 3-point bending strength, all the elements were tested at 28 days. The specimen was tested using a 25 kN (ADR Touch Control PRO 250/25) automatic operated machine. Two supports were placed under the block inset from either end, thus creating a simple supported condition. A gradually increasing load was applied to the midspan of the block at a rate of 25 kN/min until failure occurred. Failure was expected to occur due to tension at the bottom face of the sample (see Fig. 88). The machine automatically calculated the maximum 3-point bending stress in the specimens. Two compressive tests of each sample failure at the flexure were performed.
- c. For the cohesion test, the standard procedure the guide to good practice on earth construction and earth coating was applied to determine the cohesion (Savira and Suharsono, 2020). Five specimens (see Fig. 90) from each mix was made (5 x 4 x 1) cm and left to completely dry. After 28 days of drying, 2.5 kg of weight on a soft boot strap (see also Fig. 90) was hung for 30 minutes on each sample.

4.3 Mechanical properties

To understand the mechanical properties of the earthen elements, two types of tests were conducted, including for the flexural and compressive strength.

4.3.1. Flexural strength

To calculate the maximum tensile stress in the block at the point of failure, the following formula was used: $R = PL/Bd^2$. Where R is the module of rupture, P is the maximum load in N, L is the span of the length in mm, b is the average width of the specimen in mm, and d is the average depth of the specimen in mm. The flexure test was only performed on CEB and CSEB, as the sun-dried brick was excluded from this test (see Fig. 73). Traditionally, the flexural test of non-stabilised sun-dried brick does not exist, and it is negligible (Jokhio, Al-Tawil, and Syed Mohsin, 2018). The CEBs were tested at a dry ambient temperature, and the CSEBs were cured for seven days as the experiment was different: for five days, water was sprayed on the elements, and for two days they were left in a natural environment to dry. However, during the experiment, it was found that inside, the blocks were not well dried, and there was humidity. Figure 74 shows the average of the three experiments for each sample at 7 and 28 days.

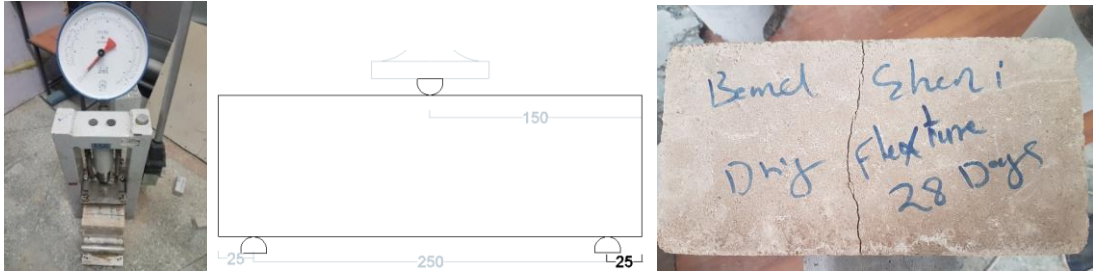


Figure 73: Procedure for flexural strength test and the occurring cracks

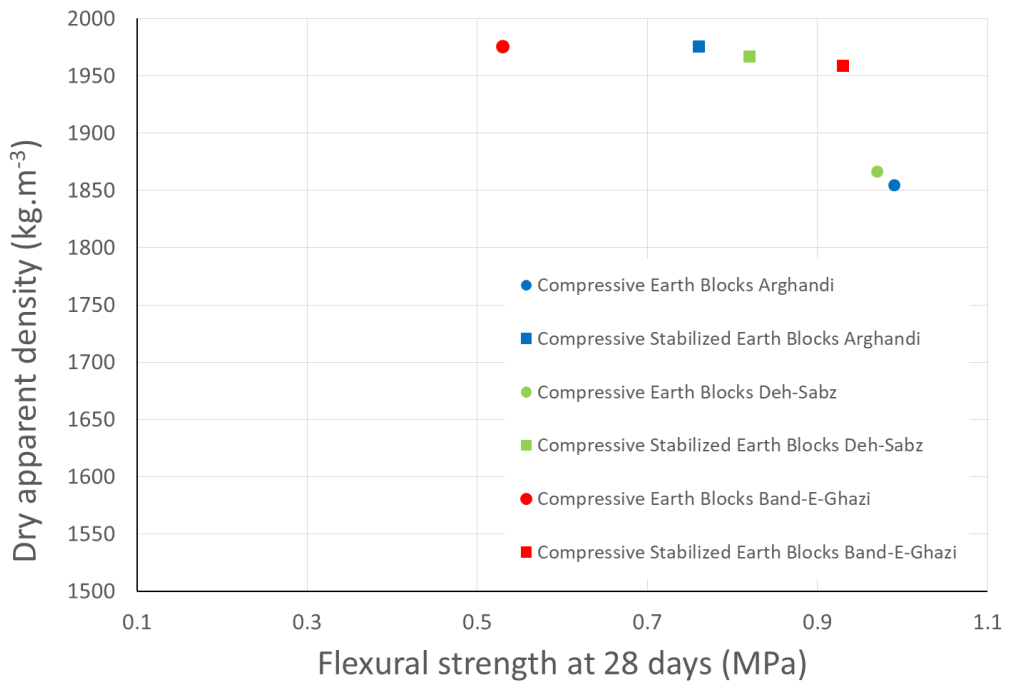
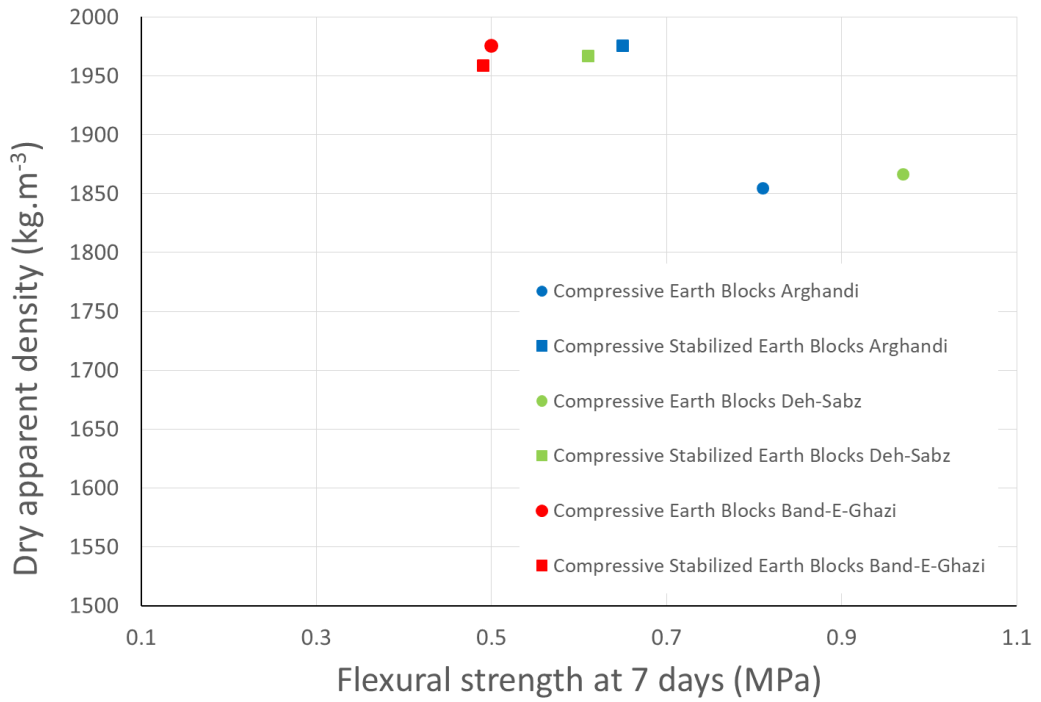


Figure 74: Flexural strength at 7 and 28 days versus dry density

The findings of this analysis show that for Deh-Sabz and Arghandi soil, their CEBs had a higher flexural strength at 7 and 28 days in contrast to the CSEBs. At 7 days, Deh-Sabz CEB had a 39 % higher flexural strength compared to Deh-Sabz CSEB; however, at 28 days, there was an increase in CSEB flexural strength, but that it was still 18 % less than the CEB. Interestingly, there was not a real change between the 7- and 28-day results for Band-e-Ghazi CEB. For Arghandi at 7 days, this increase was 16 %, and at 28 days it was 36 %. There was also a 21 % increase in CEB flexural strength at 28 days.

It can be concluded that stabilisation with cement was not really affecting the flexural strength of the pressed earth elements. In both cases, the CEBs had less dry density but better flexural strength. This confirms that the existence of finer particles in the soil can affect the flexural strength of the blocks. All the CSEBs had more sand (75 %), which did not allow for good cohesion, especially at 7 days when they were not sufficiently dried. This means that the finer the particles (CEB) such as for Deh-Sabz and Arghandi soils (98 and 93.5 %), respectively, the better the cohesion, which results in better flexural strengths in these earthen elements.

However, for Band-e-Ghazi soil, these interpretations are not applicable because for both CEB and CSEB, the sand content was the same. CEB made with Band-e-Ghazi soil had almost the same flexural strength at 7 and 28 days. However, there was a large increase (89 %) in CSEB flexural strength at 28 days. It might be due to cement hydration, and when there was more sand in the soil, it was stabilised by the cement (Minke, 2006). The results obtained during the flexural strength test seem to be within the range of results reported in the recent literature. Walker (2004) found that the dry flexural strength of CSEB was made with 5 % cement and 1.37 MPa; further, Hallal et al. (2018) reported 0.67 MPa for CEB which was stabilised with 2 % cement and 4 % lime, and Trujillo (2016) found that the dry flexural strength in soil and cement stabilised the earth blocks between 0.51 and 0.93 MPa.

4.3.2 Dry compressive strength

The compressive strength of each specimen was derived from the maximum load and original gross cross-sectional area. For Deh-Sabz and Arghandi soil, the apparent dry density of CSEB was higher than that of CEB, which was higher than the sun-dried-brick. For Band-e-Ghazi soil, the apparent dry density of CEB was higher than that of CSEB, which in turn was higher than the sun-dried-bricks. There was a good

correlation between the dry compressive strength and dry density for Deh-Sabz and Arghandi soil (see Fig. 75). Regardless of the earth element (sun-dried brick, CEB, and CSEB), those made with Deh-Sabz soil showed a better compressive strength than those made with the other two soil types (see also Fig. 75). Moreover, Regardless of soil type, the compressive strength of CSEB was higher than that of CEB, which was higher than that of the sun-dried-brick. All the compressive strengths measured were higher than 2 MPa, which constitutes a good criterion for earth construction (Burroughs, 2008).

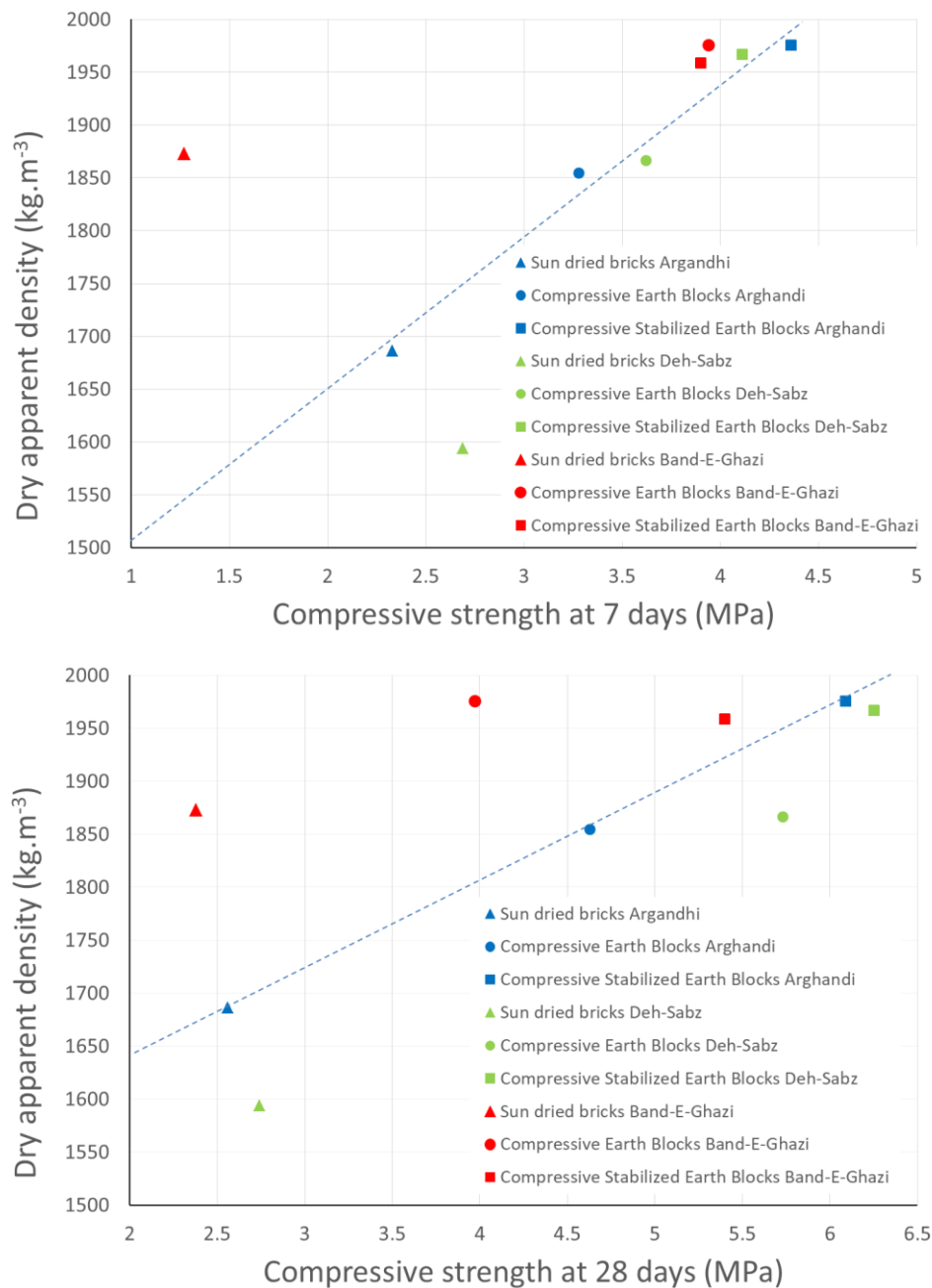


Figure 75: Compressive strength at 7 and 28 days versus apparent dry density

The results demonstrate an improvement in sun-dried brick compressive strength between 7 and 28 days. Similarly, for Band-e-Ghazi soil, the CEB results were not that different, while for CSEB, there was an improvement of 38 % in Band-e-Ghazi CSEB compressive strength. For Deh-Sabz soil, there was an enhancement of 56 % in CEB and an increase of 50 % in CSEB compressive strength at 28 days, respectively. In a similar manner, the compressive strength at 28 days increased for Arghandi elements (56 % for CEB and 52 % for CSEB). Lan and his colleagues (2021) found the compressive strength for non-stabilised sun-dried brick to be 1.62 MPa (Lan et al., 2021). Varum and Costa (2015) demonstrated that the compressive strength of bricks from ancient construction sites in Aveiro district in Portugal was between 0.7 to 2.15 MPa. For CSEB. Elahi et al. (2021) showed that it was 5.34 MPa with 10 % cement. Islam et al.'s (2020) study showed that it was 5.8 MPa for the dry compressive strength of CSEB with 10 % cement. This confirms that the compressive strength obtained during this study is in accordance with recent literature on the subject. Figure 76 below shows the CEB compressive strength testing procedure.



Figure 76: From left to right: saw cutting CEB and compressive strength test

To understand the relation between the elements and compressive strength, their porosity was analysed. The porosity of the element was derived by the division of their bulk density with their specific density ($P=1-Bd/Pd$). There was a good correlation between the sun-dried brick, CEB, and CSEB compressive strength and their porosity (see Fig. 77). Elements with more porosity (sun-dried brick) had less compressive strength, and when the porosity decreased (CEB and CSEB), the compressive strength increased (see also Fig. 77). For Deh-Sabz elements, the sun-dried brick had a 24 % higher porosity compared to CEB, which was measured as having 48 % less compressive strength. Similarly, CEB had 7 % higher porosity in comparison to CSEB, and a decrease of 9 % in compressive strength was recorded.

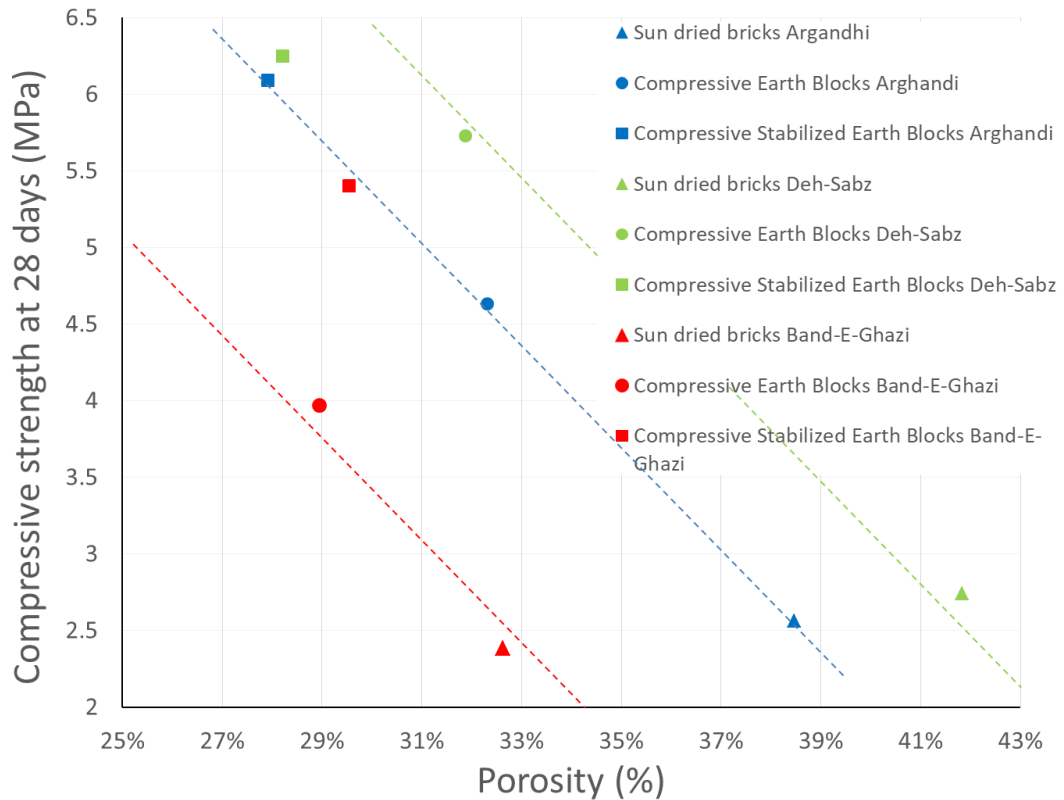


Figure 77: Elements of compressive strength versus porosity

4.4 Binder intensity index

To better understand the efficiency of soil stabilisation and its environmental impact in relation to the compressive strength gains in mechanical performance, their binder intensity index was analysed (see Fig. 78). This index b_i introduced by Damineli et al. (2010) measures the amount of binder necessary for a material in obtaining a certain compressive strength. This study proposes a simplified index of ($b_i = c/s$). The index measures the amount of binder necessary to deliver one unit of a given performance indicator (1 MPa). In this formula, c is the total consumption of binder materials, which for this study is cement (kg/m^3), and s is the performance requirement in compressive strength (MPa at 28 days). Therefore, when considering the amount of cement required to achieve 1 MPa compressive strength, the b_i index is necessary. The points on Figure 78 represent the value for the binder intensity index for sun-dried brick, CEB, CSEB, and different concretes. In this figure, the good values for the index are the small values. This figure shows that the most efficient way to use cement is in high performance concrete where the compressive strength is higher than 60 MPa. The red curve in Figure 78 corresponding to the CSEB results shows that stabilisation of earth with cement is an inefficient way to use cement. The binder index of sun-dried brick and CEB was equal to zero since they only used raw soil and water for

fabrication. The blue points are the results of the concrete tested in the laboratory. The findings of this analysis suggest that the stabilisation of raw soil with Portland cement is not advisable. This is because, it consumed large volumes of binder while providing a weak compressive strength.

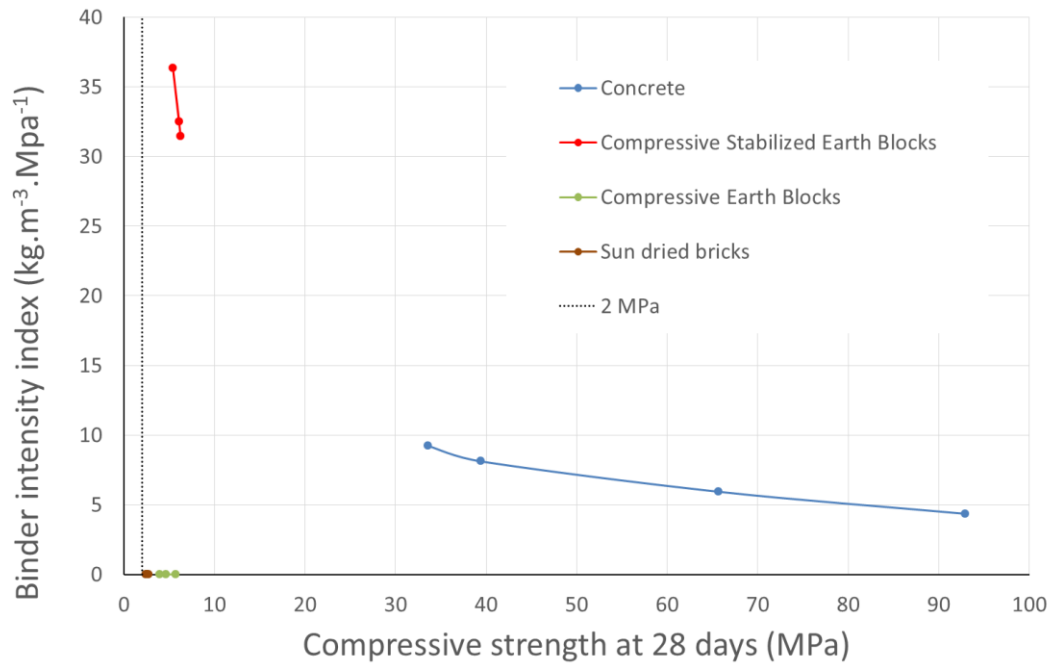


Figure 78: Binder intensity index versus compressive strength

4.5 Durability test

To find out the durability of the earthen elements, two tests were conducted for water absorption and erosion.

4.5.1 Water absorption

For the water absorption, various tests were performed, which are summarised below under separate subtitles.

4.5.1.1 Water absorption by a capillarity test (adapted from Varum et al., 2007)

This test was first conducted on the the CEB made with Deh-Sabz soil (see Fig. 79). After six hours, the CEB was eroded completely, and it was not possible to measure the water absorption by a capillarity test and/or the mass loss because all the CEB was eroded and deposited in the box. Since Deh-Sabz and Arghandi soils are similar (in petrography and texture), no further tests were conducted on Arghandi CEB. This result shows that the modified methodology used (Varum et al., 2007) was not applicable to test for Deh-Sabz CEB because it was weak against direct water contact.



Figure 79: Water absorption and mass loss test on Deh-Sabz CEB, adapted from Varum et al. (2007)

4.5.1.2 Water absorption (CSEB)

An oven-dried (110 °C) specimen was cooled to room temperature and weighted (W_1). The dried sample was immersed in 23 °C clean water for 24 hours (see Fig. 80). The specimen was then removed from the water, and traces of the water were wiped away with a damp cloth, and the specimen was reweighed (W_2). The weighing was immediately completed within 3 minutes of being removed from the water. The percentage of water absorbed in 24 hours (see Tab. 3) was calculated with this formula: $W_2 - W_1 / W_1 * 100$. After 24 hours in water, the CSEBs were in a good condition, and no cracks or erosion were recorded.



Figure 80: CSEB after 24 hours fully immersed in water

Block types	Dry weight/gr	Weight after 24 hours in water/gr	Water absorbed (%)
Band-e-Ghazi	9108	10182	11,79
Deh-Sabz	9147	10200	11,51
Arghandi	9185	10206	11,11

Table 3: Percentage of water absorption for CSEB after 24 hours of immersion in water (ASTM, 2017)

It was found that all the CSEBs were absorbed by a similar percentage of water. The results of the experiment was compared with Auroville Earth Institute's (2020) findings on CSEB. The institute has a classification system based on the percentage of water that stabilises a block after 24 hours of being fully immersed in water. The

classifications are: A (8-10 %); B (10-12 %); and C (12-15 %). The results confirm that all the CSEBs match Classification B of Auroville Earth Institute (2020). This category had a flexure strength of between 0.4 to 0.8 MPa, a dry compressive strength of 4 to 5 MPa, 10 to 12 % water absorption, and an apparent bulk density of 1,800-1,900 Kg/m³.

4.5.1.3. Water absorption (sun-dried brick and CEB)

The presence of clay in the earth elements hugely affects water uptake. Clay made up of thin layers of crystallised structures and complex clay minerals have a negative charge on the surface, which attracts water easily (Houben and Guillard, 2014). A preliminary water absorption test was performed to understand the behaviour of non-stabilised earth elements in contact with a considerable amount of water to analyse the damage associated with water. The samples (sun-dried brick and CEB) were placed on top of saturated cotton (see Fig. 81), and after 24 hours the amount of water absorbed was analysed.



Figure 81: Visual inspection of sun-dried brick and CEB surfaces, after 24 hours on unsaturated cotton

In 24 hours, the sun-dried brick specimen mass had increased by the following: Deh-Sabz (4.77 %), Arghandi (5.85 %), and Band-e-Ghazi (6.9 %). The average capillary height for the sun-dried brick after 24 hours was 5, 5.5, and 8 cm, respectively. While after 24 hours, the CEBs specimens' mass had increased to 3.66 %, 4.11 %, and 8.43 % for Deh-Sabz, Arghandi, and Band-e-Ghazi, respectively. The average capillary height after 24 hours was 7, 7.5, and 22 cm, respectively. Based on the visual examination of the six specimen's surface on both sun-dried brick and CEB earth elements, no evidence of mass loss, deformation, or cracking was observed. The results show that the sun-dried brick made with Band-e-Ghazi soil had the highest water absorption capacity (6.29 %). Arghandi had the second highest absorbing capacity (5.85 %), and Deh-Sabz had the lowest water absorption capacity (4.77 %).

The higher water absorption in Band-e-Ghazi elements could be due to the higher sand content (45.85 %). The remaining 54.15 % clay and silt parts mostly stuck to each other and formed small clods, rather than soft particles. This resulted in more pores in the Band-e-Ghazi elements, especially in the CEB, while the two other soils had a finer texture and a smaller number of pores. Porosity is proportional to hydraulic conductivity since the higher the number of pores, the more water conductivity that occurs.

There has been several studies on water absorption and capillarity tests on *treated* earth elements and exterior earth plaster (Coroado et al., n.d; Varum et al., 2007). The usual stabiliser for soil is cement, lime, and certain chemical materials. However, when dealing with *untreated* earth elements, there is a scarcity of literature and existing standardised codes on this. Fortunately, it was possible to find a recent study by Ribeiro (2020). In this paper, she measured the water absorption by the use of a capillarity test on sun-dried brick and RE before and after treatment. Two areas in the south of Portugal were studied: Montemor-Novo for sun-dried-brick constructions and Cercal for RE constructions. The *untreated* earthen element water absorption was similar to the results obtained in this research. They followed the code EN 15801: 2008, with three samples of sun-dried brick and RE placed on top of absorbent paper, and their water absorption was measured by a capillarity test at 30 minutes and 3, 24, and 72 hours. Their results after 24 hours were aligned with this research. The sun-dried bricks were compared to the sun-dried brick, and the RE was compared to the CEB in this research. Their findings showed that the brick mass had increased 10 % in 24 hours, but that the RE had a 5 % increase in mass.

There was an increase of 52.3 %, 41.5 %, and 37.1 % in mass in the sun-dried bricks' capillary rises on account of the water absorption in the Ribeiro (2020) study, compared to Deh-Sabz, Arghandi, and Band-e-Ghazi sun-dried brick, respectively (see Fig. 82). This increase in mass could either be due to the use of different absorbent materials (natural cotton and absorbent paper), soil petrography, or the variation in texture in those elements. The sun-dried bricks studied by Ribeiro (2020) had 58 % sand, while Deh-Sabz, Arghandi, and Band-e-Ghazi bricks had 2 %, 6.3 %, and 45.8 % sand, respectively. However, in comparing the CEBs with the Ribeiro (2020) study, even though the use of different absorbency might be an issue, it was possible to find a correlation between the results. Band-e-Ghazi CEB showed a similar capillary, while

for Deh-Sabz 26.8 % and Arghandi 17.8 % less water absorption was recorded (see Fig. 82).

The results of water absorption from the capillarity tests for CEBs indicate that the elements made with Band-e-Ghazi soil absorbed more water in contrast to the Deh-Sabz and Arghandi elements. Therefore, no further water absorption experiment was necessary for Band-e-Ghazi. However, it was not easy to distinguish between Deh-Sabz and Arghandi because they had an extremely similar water absorption capacity, thus further tests are required to clarify this.

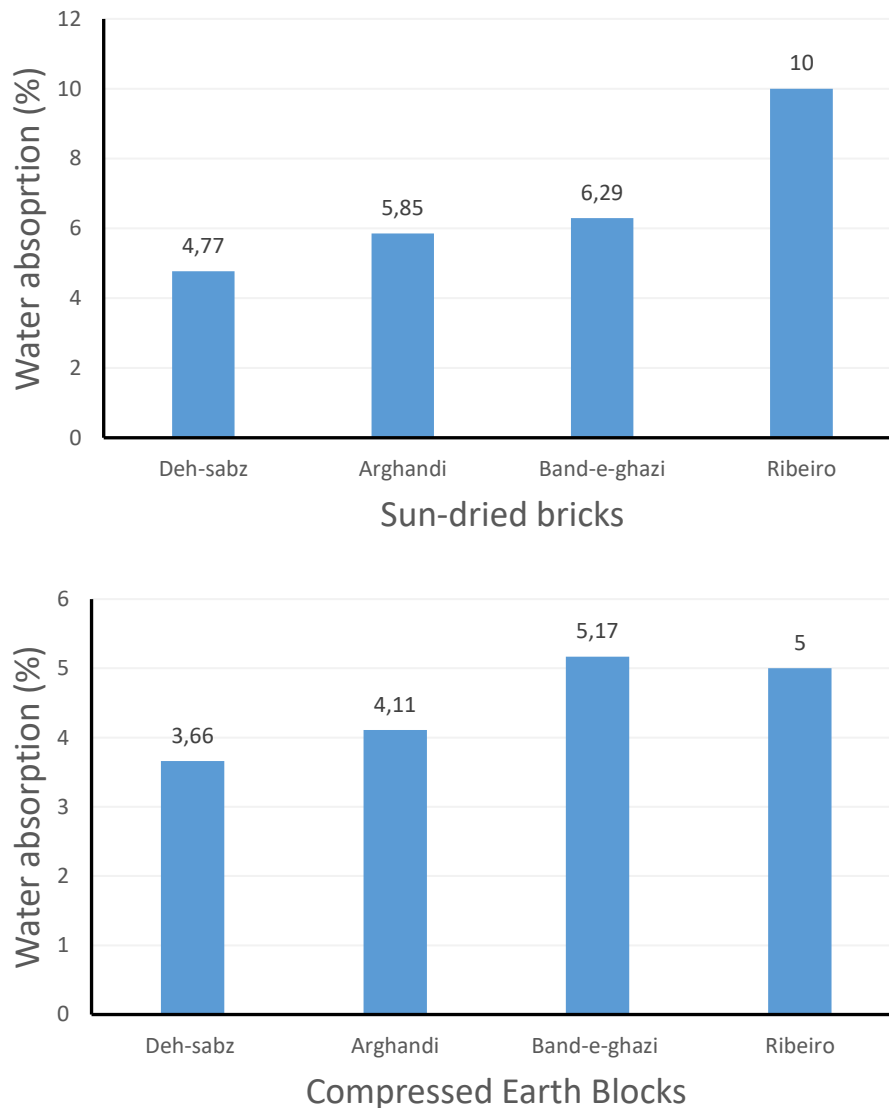


Figure 82: Sun-dried brick and CEB water absorption from the capillarity test, after 24 hours on unsaturated cotton

Further capillarity tests on Deh-Sabz and Arghandi CEBs were conducted on a sample of CEB (see Fig. 83), which was dry weighted (p_0) and then immersed in 5 mm of water for 10 minutes; then, it was removed from the water and reweighted (p_1). With

this data, two calculations were made: 1) The percentages of water absorbed by the capillarity test; and 2) the coefficient of resistance to the capillary rise ($C_b = (p_1 - p_0) * 100 / s \sqrt{10}$. S = block surface area in direct contact with water. It is considered that a block has a weak capillary when $C_b \leq 20$, and a block has a weak capillary when $C_b < 40$.



Figure 83: Water absorption and mass loss test (10 and 60 minutes) face down in water on Deh-Sabz CEB

After a 10- and 60-minute immersion into water, a significant amount of Deh-Sabz CEB was deposited in the box (11.4 and 19.5) %, respectively. This confirms that when the CEB was in direct contact with water, it absorbed a lot of water and eroded in a short period of time. Deh-Sabz CEB had a resistance coefficient of $C_b = 56.5$ at 10 minutes and $C_b = 70.54$ at 60 minutes (see Tab. 4), and it had a low capillarity coefficient. It was also found that this CEB rapidly absorbed water in the first 10 minutes when in the water, but that after this period, the absorption process was slow. The results showed 9.38 % and 11.79 % water absorption at 10 and 60 minutes of immersion into water (see also Tab. 4). However, Arghandi CEB had comparatively better results in both water absorption and its coefficient of resistance to the capillary rise, especially in the 10-minute immersion in water. During this period, 4.46 % water was absorbed, which shows a decrease of 110 % in water absorption compared to Deh-Sabz (see Tab. 4 and 5). C_b showed a decrease of 107 % and 173 % for the dry erosion (see Tab. 5). However, the same tests performed over 60 minutes had similar results to Deh-Sabz CEB, except for the dry erosion. Decreases of 5% in total water absorption, 3 % in C_b , and 64 % in dry erosion were also recorded.

No	Time	Dry weight /gr	Wet weight /gr	Block surface in water/cm ²	Wet eroded soil/gr	Dry eroded soil/gr	% of dry erosion	Height of humidity/mm	Total water absorbed %	Coefficient of resistance to the capillarity rise (C_b)
1	10	8706	7903	457.25	1620	1000	11,4	3	9,38	56,5
2	60	8658	7274	//	2404	1691	19,5	6,27	11,79	70,54

Table 4: Water absorption and coefficient of resistance to the capillary rise for Deh-Sabz CEB

No	Time	Dry weight / gr	Wet weight /gr	Block surface in water/cm ²	Wet eroded soil/gr	Dry eroded soil/gr	% of dry erosion	Height of humidity/mm	Total water absorbed %	Coefficient of resistance to the capillarity rise (Cb)
1	10	8860	8755	457,25	501	370	4.17	3	4.46	27,38
2	60	8825	8401	//	1413	1050	11,89	6,25	11,2	68,39

Table 5: Water absorption and coefficient of resistance to the capillarity rise for Arghandi CEB

It could be concluded that both CEBs were weak against direct contact with running water. They were able to absorb a great volume of water, especially during the first 10 minutes, and that their coefficient of resistance to the capillarity rise was weak. Therefore, they have to be protected from running water.

4.5.2 Erosion test

To better understand the durability of the CEBs, in addition to the water absorption test, resistance to an abrasion test was conducted on Deh-Sabz and Arghandi CEBs. The abrasion coefficients (Ca) of the CEB that represent the loss of the material due to brushing on an abrasive surface was calculated with the following formula: $Ca = \frac{S}{m_0 - m_1}$ [cm²/g]. Where:

Ca = block coefficient of abrasion,

S = brick abrasion area in cm² (S = L x I where L = the length of the brushed face of the block and I = the brush width),

m₀ = initial mass of the brick before abrasion in grams, and

m₁ = mass of the brick after the abrasion test in grams.

The result of the coefficient test for Deh-Sabz and Arghandi CEBs are 10.5 and 8.2, respectively. The standard indicates the basic coefficients to be able to classify an earth block according to its abrasion resistance (see Tab. 6). The higher the abrasion coefficient of a block, the better resistance it has.

Solid block	BTC 20	BTC 40	BTC 60
Minimum abrasion coefficient (Ca) cm ² /g	2	5	7

Table 6: Abrasion resistance of BTC (AFNOR - XP P13-901, 2001)

Comparing the two CEBs with the standard, both had a high abrasion coefficient, Deh-Sabz had a higher abrasion coefficient of 22 %, compared to Arghandi CEB, and 110 % higher than BTC 40. The NF XP X 13-901 standard was considered for a BTC 40 block with a good abrasion coefficient (see Fig. 84). This test confirmed that both

CEBs had a good abrasion resistance. Abrasion is the ability of the CEB to resist against surface erosion and scratches when it is in direct contact with other elements. This is more important when the CEB is applied in the interior façade of the walls where abrasion occurs regularly, especially by furniture.

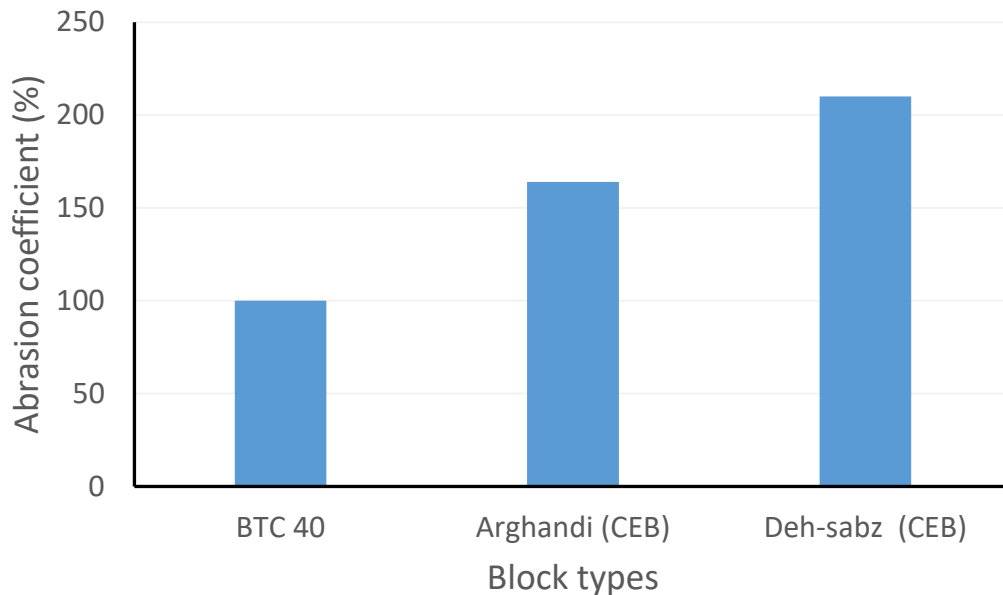


Figure 84: Deh-Sabz and Arghandi versus BTC-40 block abrasion coefficient

4.6 Thermal property

As previously mentioned, in traditional mud housing, the walls act as a natural insulator, keeping them warm in the winters and cool in the summers. Earth-made houses with a high thermal mass structure is efficient in creating a comfortable indoor environment during both seasons. However, there is a need for energy during all seasons in Kabul, but there is an increased energy demand during winters in comparison to the summers. For this reason, the thermal properties of the elements made from the three soils were analysed. Unfortunately, as with other properties of the earthen elements, the thermal properties of the bricks and blocks have not been studied in Afghanistan, identifying a gap in the literature. To the author's best knowledge, this is the first study on the thermal property of such elements. All the experiments were performed in a machine at Herat University, the only one in Afghanistan (ISOMET Model 2104, heat transfer analyser). Dry samples aged three months of sun-dried brick, CEB, and CSEB were tested. The results of these measures are given in Figure 85. The dashed green and blue lines are the mean thermal conductivity for the Deh-Sabz and Arghandi elements.

Arghandi earthen elements had the lowest thermal conductivity whereas Deh-Sabz had the highest thermal conductivity, especially for sun-dried brick, but they had relatively less compressive strength compared to Deh-Sabz. The high thermal conductivity for Deh-Sabz sun-dried brick might be due to the uneven surface of the specimen, since the ISOMET Model 2104 machine is sensitive, and if the entire surface of the instrument is not in contact with the specimen surface, this might change the result. The existence of humidity in the sample could also be a reason for such a high thermal conductivity because the specimens were transported from Kabul to Herat by public transport, which took several days. The mean thermal conductivity of Deh-Sabz earthen elements was 20 % higher than that of Argandhi earthen elements and 24 times higher than the thermal conductivity of glass-wool insulation. Hence, there is a need for insulation in Kabul's affordable housing design. A prefabricated panel from a mixture of clay and wheat straw has been developed and applied for insulation purposes.

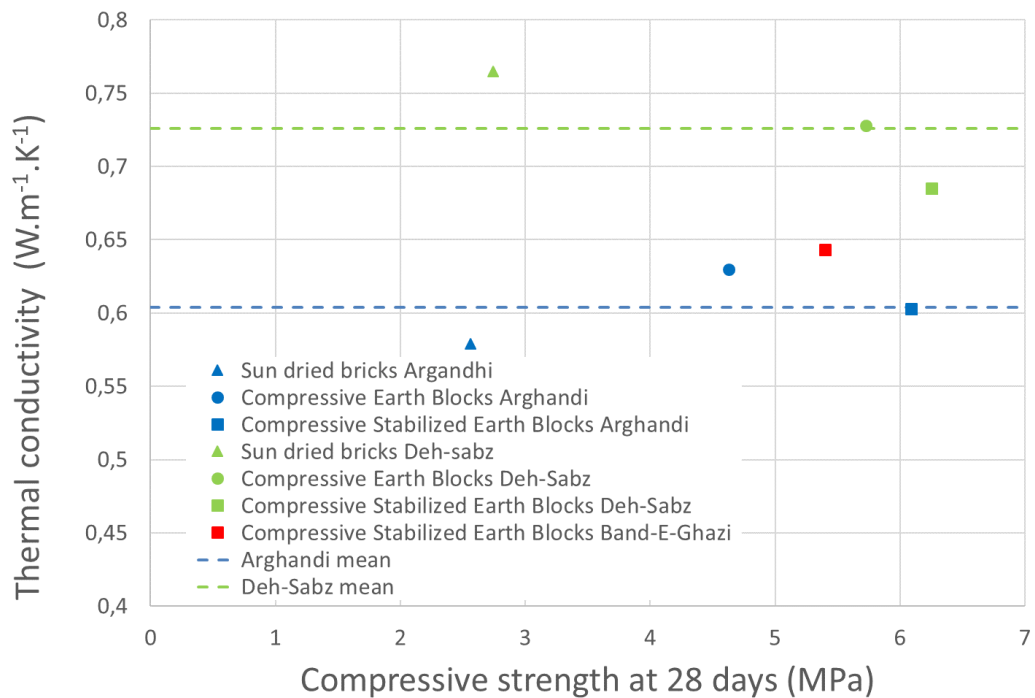


Figure 85: Thermal conductivity versus compressive strength

The results were compared with the recent literature on earthen element thermal properties. Mayotte (2018) indicates that the thermal conductivity of an earth block is usually 0.42 to 1 W/m.K, with an average of 0.8 W/mK. The results obtained during this study for bricks and blocks fit into this interval. AFNOR (2001) determined the

thermal conductivity of an earth block at 0.5 W/m.K. In Lavras, Brazil, a study found the thermal conductivity of natural sun-dried brick to be 0.85 W/mK, and when the brick was stabilised with Synthetic Termite Saliva, the thermal conductivity increased to 0.87 W/mK (Gandia et al., 2019). Moussa et. al. (2017) has studied the thermal conductivity of eight artisanal cement stabilised earth block companies in Senegal, and they found different thermal conductivities for various block-producing companies, ranging from 0.66 to 0.86 W/mK (Touré et al., 2017). Their literature review indicates that the thermal conductivity of the studied earth elements in this research is in accordance with the recent literature.

However, other studies found a very low thermal conductivity value for bricks. El Azhary et al. (2018) studied the thermal behaviour of unfired bricks in Morocco in three different regions, namely Tamansort, Essaouira, and Marrakech; further the thermal conductivity of these bricks for each of the regions was recorded as 0.35, 0.365, and 0.457, respectively. Another research implemented in Peru shows the thermal conductivity of three regions' sun-dried bricks, stabilised with wheat and barley straw. By adding 2.5 % of mixed wheat and barley straw, the thermal conductivity of the bricks was 0.316 and 0.24; when mixed with 1.5 % of straw, the thermal conductivity increased to 0.334 (Abanto et al., 2017). The last two studies were conducted with the guarded hot plate and heat flow metre methods for analysing the thermal conductivity, which is not the same method used for this study.

Soil has a good volume heat capacity and the ability to damp and delay thermal conduction and external temperature flow into the interior (Houben and Guillard, 2014). Figure 86 shows that there was a good correlation between the three soils specific heat transfer capacity and apparent dry density. As the dry density increased, the specific heat transfer capacity decreased. This decrease was more important when cement was used for stabilisation. Regardless of the earth element used (sun dried brick, CEB, and CSEB), elements made with Deh-Sabz soil had an average specific heat transfer capacity of 6 %, higher than that of elements made with Arghandi soil.

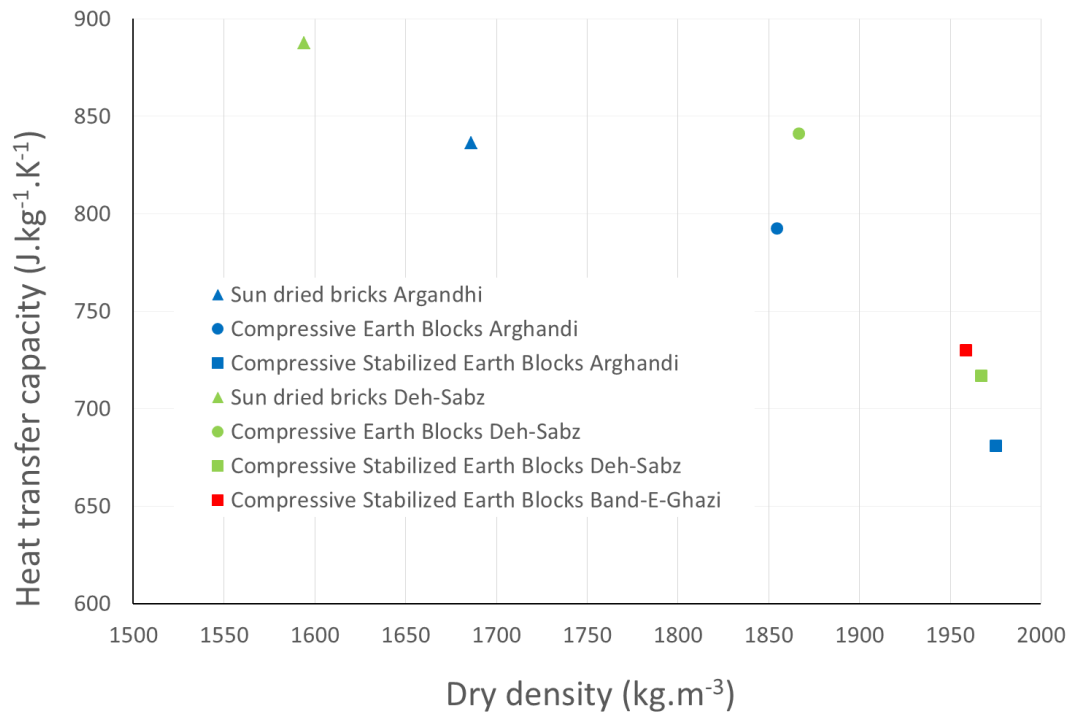


Figure 86: Thermal conductivity versus compressive strength

4.7 Selection of the best earthen elements

This study compared three types of earthen elements (sun dried brick, CEB, and CSEB) made with three different soils in the Kabul region (Arghandi, Band-e-Ghazi, and Deh-Sabz). The following results were obtained:

- Considering the environmental issues, the stabilisation of earth with Portland cement was not efficient neither in mechanical, nor in environmental terms, since the consumption of a large amount of cement provided a weak compressive strength.
- From the soil studied, the dry compressive strength of CEB was mostly higher than that of sun-dried brick, while the thermal conductivity of both was similar. The results showed a significant increase of 81 % for Arghandi soil, 67 % for Band-e-Ghazi soil, and 109 % for Deh-Sabz soil. This means that the most suitable earth element for the production of mud brick in Kabul is CEB.
- Considering the three soils, the dry compressive strength of Band-e-Ghazi CEB was 31 % weaker than that of Deh-Sabz CEB, and it was 14 % weaker than that of Arghandi. Because of the weak compressive strength, this soil has not been selected. To conclude, for the other two soils, it was not easy as for Deh-Sabz soil, the dry compressive strength was 24 % higher than that of Arghandi, but the

thermal conductivity was 16 % higher than Arghandi. Taking into account the value of the thermal conductivity which does not allow CEB to be classified in the family of insulating materials, Deh-Sabz soil has been selected as the most suitable soil for the construction of affordable earth housing in Kabul.

- The results of the abrasion coefficient test for Deh-Sabz and Arghandi CEB confirm that the blocks had a high resistance to abrasion (10.5 and 8.2 cm²/g, respectively).
- However, the results of the water absorption test on Deh-Sabz CEB confirmed a low capillary coefficient of resistant to water, and this element was very weak against direct contact with running water and could potentially collapse after a few minutes of contact. Therefore, affordable housing made with the CEB has to be equipped with a rigid concrete or stone foundation, and the walls (partition and other walls) must be kept away from running water and humidity. The exterior walls of the building need to be protected with a stabilised plaster, with either wheat straw or chemical-water repellent. Similar precaution needs to be taken for the roof of the house.

4.8 Experiments on mortar

4.8.1 Mixture proportion and crack test

The objective is to find a soil- and sand-based masonry mortar that is able to effect a masonry assembly of the selected CEB. This mortar must have a suitable workability, sufficient mechanical strength, and the desired shrinkage limits. A matrix of nine design mixes from Deh-Sabz soil was prepared (see Tab. 7); the first observation was made to find a crack in the mixture, containing a mix of a soil and sand ratio of 1:1 (see Fig. 87), which showed cracks with any percentage of water. However, a mix with one volume of soil and two volumes of sand had cracks with 20 % water, but no cracks were observed with 25 % and 30 % water (see also Fig. 87). Moreover, for a soil and sand ratio of 1:3, the same observation was seen as for the 1:2 soil and sand ratio (see also Fig. 87). The analysis shows that five of the mixes had cracks, and so they were excluded from further analyses. However, four of them (A, B, C, and D) had no cracks, and this confirms that they are good to use as mortar and for the interior wall plaster (see also Fig. 87). This four-mix design was physically analysed to find its workability in practice; the mix designs C and D were rather liquid, which affected their workability and consistency. It was difficult to lay them as mortar or as plaster because they contained a lot of water. At this stage, mortar C and D were also rejected. Hence, two mix designs (A and B) remained. However, after further analysis, such as

the flexural and compressive strength and cohesion tests, it was possible to choose between the two mix designs.

Water content %	20 %	25 %	30 %
1 Volume of Soil +1 Volume of Sand	1 kg Deh-Sabz 1 kg River Sand 0.4 kg Water	1 kg Deh-Sabz 1 kg River Sand 0.5 kg Water	1 kg Deh-Sabz 1 kg River Sand 0.6 kg Water
1 Volume of Soil +2 Volume of Sand	1 kg Deh-Sabz 2 kg River Sand 0.6 kg Water	1 kg Deh-Sabz 2 kg River Sand 0.75 kg Water	1 kg Deh-Sabz 2 kg River Sand 0.9 kg Water
1 Volume of Soil +3 Volume of Sand	1 kg Deh-Sabz 3 kg River Sand 0.8 kg Water	1 kg Deh-Sabz 3 kg River Sand 1 kg Water	1 kg Deh-Sabz 3 kg River Sand 1.2 kg Water

Table 7: Matrix of nine-mixtures with various soil, sand, and water ratios



Figure 87: Grid of nine mixtures after a 28-day drying period

4.8.2 Strengths (flexural and compressive)

Three standard specimens (40.1 x 40 x 160 mm) from the mix designs A and B were prepared. After demoulding, the specimens were weighted and measured with a calliper, and before the mechanical tests at 28 days, the specimens were reweighted and measured to find their shrinkage and apparent density (see Tabs. 8 and 9). The average linear shrinkage for both mix designs was less than 6 % (see also Tabs. 8 and 9), which represents the characteristics of good soil for construction and compaction

(Burroughs, 2008). The average 28-day drying for the shrinkage for mix A was 4.33 % and for mix B was 2.93 %, which shows a shrinkage increase of 47 % in mix A (see also Tabs. 8 and 9). The apparent dry density for mix A is relatively higher (1,852.7 kg/m³) in comparison to the (1836.3 kg/m³) density for mix B.

Wet samples after 48 hours of demoulding

Sample made with mix design A

Date: 11-07-2021

Samples	Dimension/mm			Mass/ gr	MV's kg/m ³	Linear Shrinkage %
	L	B	H			
A1	154.9	39.5	37.2	454.9	1998.5	3.18
A2	154.5	38.9	37.2	458.8	2052	3.44
A3	154	39.5	37.5	456.98	2003	3.75

Dry samples after 28 days of demoulding

Sample made with mix design A

Date: 09-08-2021

Samples	Dimension/mm			Mass/ gr	MV's kg/m ³	Linear Shrinkage %
	L	B	H			
A1	153.2	38.9	37	402.31	1824.5	4.25
A2	153	38.8	36.9	407.86	1861.9	4.37
A3	153	38.4	37	406.88	1871.7	4.37

Table 8: Specimens A1-A3, shrinkage and density at 2 and 28 days

Wet samples after 48 hours of demoulding

Sample made with mix design B

Date: 11-07-2021

Samples	Dimension/mm			Mass/ gr	MV's gk/m ³	Linear Shrinkage %
	L	B	H			
B1	157	39.15	36.2	451.8	2,030	1.87
B2	155.5	39.2	37	459.1	2,035	2.81
B3	156.5	39.5	36.9	456.38	2,001	2.18

Dry samples after 28 days of demoulding

Sample made with mix design B

Date: 09-08-2021

Samples	Dimension/mm			Mass/ gr	MV's gk/m ³	Linear Shrinkage %
	L	B	H			
B1	155.3	39	36	402.5	1845.9	2.93
B2	155.4	39.1	37	406.84	1809,6	2.87
B3	155.2	39	36.5	404.9	1832.7	3

Table 9: Specimens B1-B3, shrinkage and density at 2 and 28 days

All six samples (mix designs A and B) were tested for their flexural strength, and with this test, certain elements of resistance to deformation were found. The results showed that the average of the three samples' flexural strength for mix design A was 12 % higher than that for mix design B (see Fig. 88). This might be due to the use of a different mix design and the various soil and sand ratios. There was more sand in mix B (75 %) and comparatively less sand in mix A (66.6 %). The increase in sand affected the cohesion of the element, which in turn resulted in a low flexural strength.

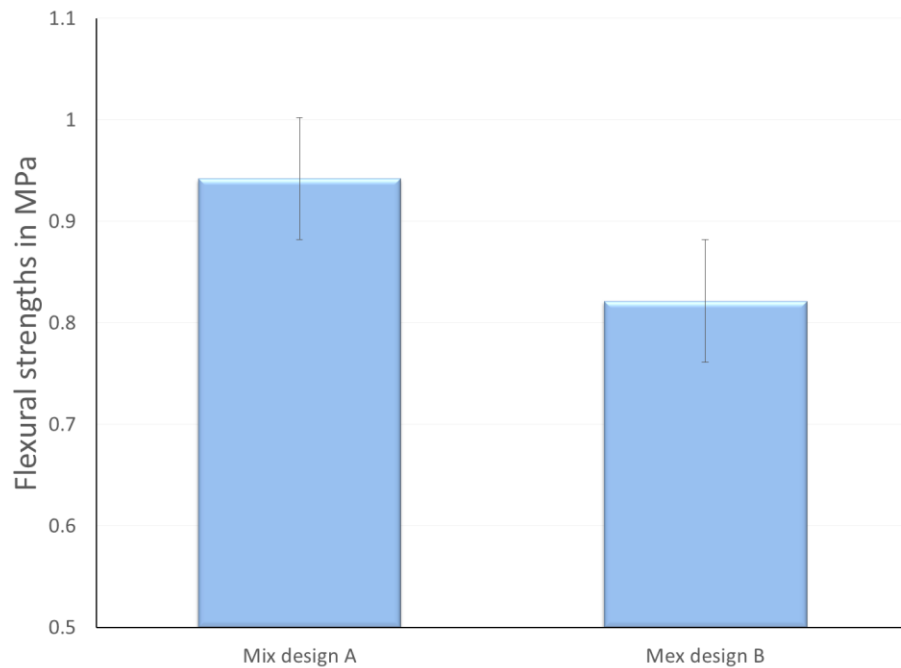


Figure 88: Mix designs A & B flexural strength at 28 days of drying

After each flexural test, two compressive strength tests on the same sample were conducted, and the average of the six specimens' compressive strength for mix A and for mix B is shown in Figure 89. The compressive strength of each specimen was

derived from the maximum load and the original gross cross-sectional area. The relatively higher dry density and more soil content (a better cohesion) in mix A resulted in a higher compressive strength. Considering the two mix designs, the dry compressive and flexural strength of mix A was 24 % and 12 % higher than that of mix B, respectively. Therefore, this mortar was selected for this study.

The results of this study are in line with other literature on the subject. For instance, Bei and Papayianni (2003) studied three different mixtures of soil and sand ratio (1:10, 2:10, and 3:10). They found the flexural strength to be between (1.13 and 1.83) MPa, and the compressive strength between (1.94 and 3.21) MPa. Another study by Walker (1999) on the soil and sand ratio (1.5:10) with a 5 % cement mortar shows 1.2 MPa, with 10 % cement and a compressive strength of 3.4 MPa.

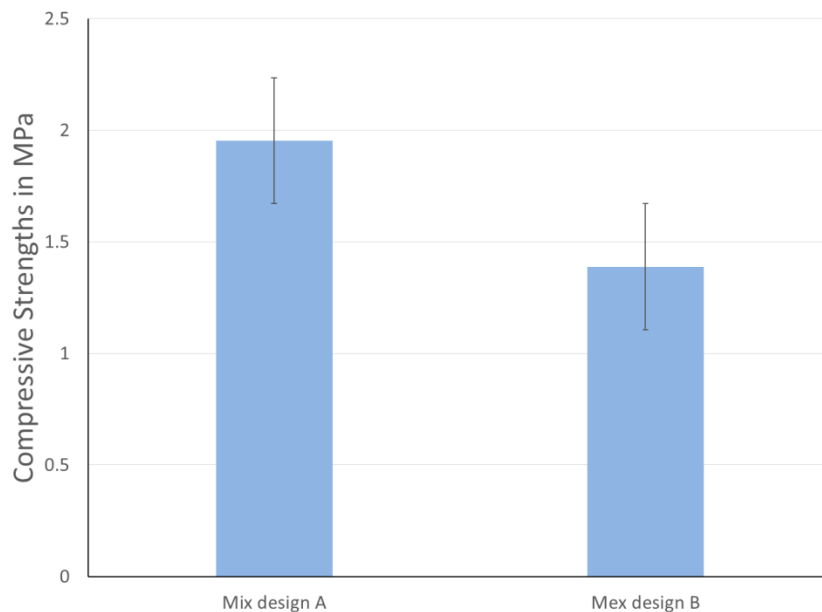


Figure 89: Mix designs A & B compressive strength at 28 days of drying

4.8.3 Cohesion

A cohesion test was conducted on the specimens made with mixtures A and B. All the five samples were able to tolerate the weight for 30 minutes, and when the weight was left for longer, at 60 minutes, the specimens were able to tolerate this weight as well (see Fig. 90). The result confirms that the elements made with both mixes (A and B) had a good cohesion to be used as a mortar for making the walls and interior plaster. Although mix B had a good cohesion, it was not used for this study due to its weaker flexural and compressive strength compared to mix A.



Figure 90: Mortar cohesion test procedure

4.9 Structure wall from the selected mortar and CEB

4.9.1 Design and fabrication

The selected mortar (mix design A) made it possible to choose the manufacturing mortar for making CEB walls. This study has focused on the realisation of two sizes of wallets (see Fig. 91) to obtain the slenderness of 1 (wall 1) and the slenderness of 2 (wall 2). The first system of the low-wall (wall 1) layout is a so-called triplet-type system; it consists of two whole CEBs at the base of the wall, two CEBs on the top

laid in opposite directions, bonded by 10 mm of mortar horizontally and vertically, and with two more CEBs laid at the top, parallel to the base wall, and bounded with a second layer of mortar. The whole of this triplet made it possible to obtain a test piece of the dimensions 300 mm in length, 300 mm in width, and 320 mm in height. The second type of the low wall tested in compressive strength is wall 2, with a whole CEB at the base of the wall; then, at the second layer, a CEB was divided into two identical parts and partly bonded by 10 mm of mortar, horizontally and vertically, at the building joints, and also in the upper part with a complete CEB. The whole of this triplet made it possible to obtain a test piece of the dimensions 300 mm in length, 145 mm in width, and 320 mm in height (see also Fig. 91). A steel plate, 300 mm in length, 300 mm in width, and 10 mm in height, was used as a cup at the bottom and top of the walls to distribute the load on the entire wall surface.

After manufacturing, the walls were stored in the laboratory for two months, and they were well-dried and then tested under compression. The original plan was to conduct more tests on the higher walls (six layers of CEB) as well, with the slenderness of 2 for wall 1 and the slenderness of 4 for wall 2. Unfortunately, in Kabul, it was not possible to find a compressive machine that would be able to test walls higher than 340 mm. Therefore, the maximum height of the wall was limited to 340 mm. After a two-month drying period, a few small cracks were observed in the wall 1 mortar, where mortar joins two horizontal CEBs. This could be due to the bond strength, which depends on the block moisture content during construction. The CEB face should have been wet before applying the mortar because when CEB is dry, the water is sucked rapidly out of the mortar and prevents the required adhesion and proper bonding of the units (Walker, 1999; Jayasinghe and Mallawaarachchi, 2009).



Figure 91: CEB walls: slenderness 1 and 2

4.9.2 Results of the tests

The objective was to measure the compressive strength of the two walls made with Deh-Sabz CEB and to compare the behaviour of the blocks with respect to their slenderness. The compressive strength of the low walls was measured using a semi-automatic ADR-2000 BS concrete cube-testing machine, with a 250 kN pressing capacity. The compressive strength of the wall was derived from the maximum load and original, gross cross-sectional area of the wall. The tests were carried out under constant loading. This test was performed in accordance with the NF EN 1052-1 (1998) standard tests on building walls. This standards recommend a loading speed of 0.15 N/(mm².min) for a wall of 145 mm in width and 0.3 N/(mm².min) for a wall of 300 mm in width, which made it possible to obtain a long destructive test in the given time (with a test duration of between 15 and 30 minutes, depending on the stacking).

The time duration was respected during the test; 18 and 17 minutes were recorded for wall 1 and wall 2, respectively. 10 mm of steel plates were used to cap both sides of the wall to ensure the flatness of the loading surface because it did not have sufficient rigidity. The compressive strength obtained during these experiments is shown in Figure 92. During the test, it was found that the steel plates used as caps were not flat enough. The steel plates were cut by a hydraulic press metal cutting machine, which resulted in uneven surfaces, especially on the edges. The compressive strength could have been more than the value obtained, especially for wall 1 (slenderness 1), with more area facing the steel plates. However, for wall 2, only the centre and the flatter part of the plates touched the wall, and this might be the reason for better compressive strength for wall 2. There is literature on testing the compressive strength of earth-made bricks (Varum et al., 2007), and which has evaluated the compressive strength of traditional adobe walls in Portugal. Thirteen wallets of dimensions (17 x 17 x 100) cm³ were constructed at a reduced scale 1:3 and tested under compression, perpendicular and diagonal to the bed-joint. The results showed a compressive strength of between (0.77 and 1.57) MPa and (0.05 and 0.19) MPa, respectively.

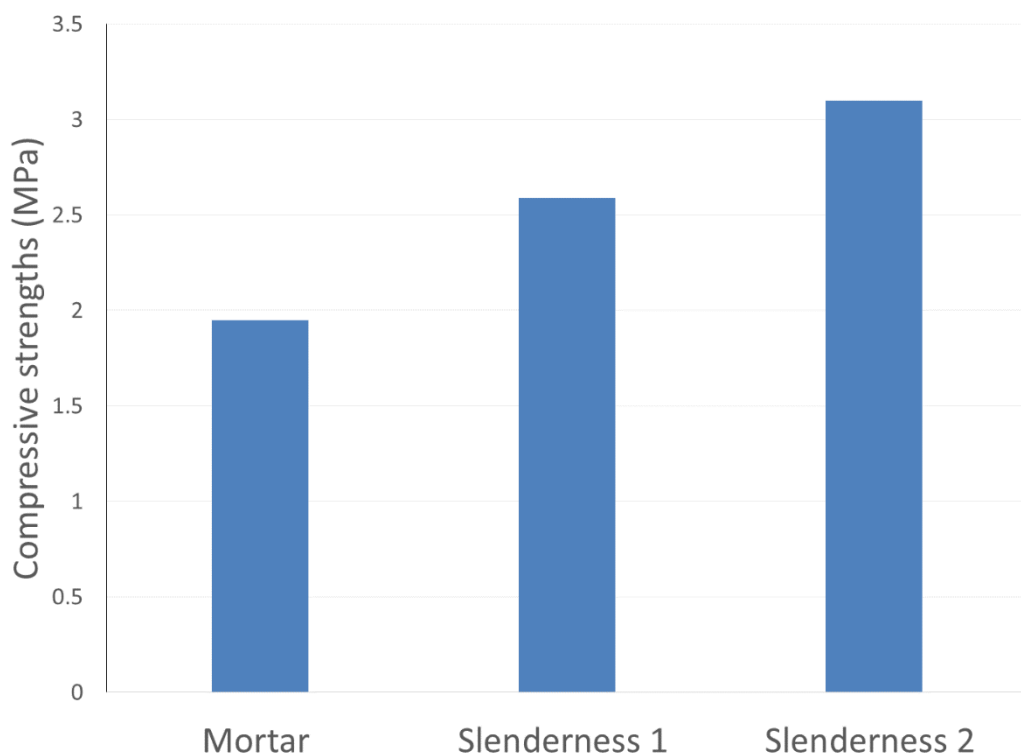


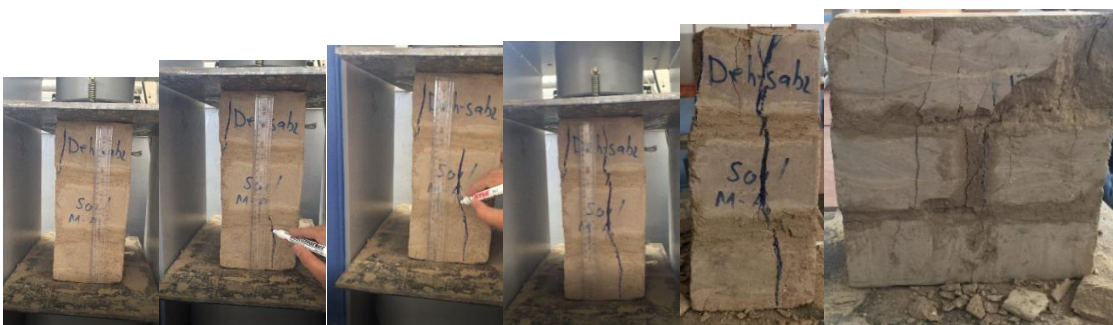
Figure 92: Wall's compressive strength: slenderness 1 and 2

In wall 1, the crack started along the vertical mortar where two horizontal and vertical CEBs were joined (see Fig. 93). This pattern continued to the top and bottom CEBs; most of the cracks occurred in the middle and bottom CEBs, while the top CEB had only one crack when the wall collapsed. There were more cracks on the right side of the wall, compared to the left side (see also Fig. 93); until the failure of the wall, only one small crack was observed at the left bottom CEB. This confirms that the steel surface was not flat; otherwise, the cracks should have occurred on the left side of the wall as well. However, for wall 2, the crack started with the bottom CEB, which continued to the mortar and to the middle and top CEBs (see Fig. 94). The cracks in wall 2 were created systematically, and all the CEBs and mortar had cracks one after another. The same organisation of the cracks was seen in the west and east elevation of the wall (see also Fig. 94). The occurrence of the cracks in the wall 2 confirms the flatness of the caps on both sides of the specimen.



Load in kN: 109 180 220 225,4

Figure 93: Crack pattern and maximum load (kN) when cracks were observed in the compressive test (wall 1)



Load in kN: 91 130 134 134,4 134,4

Figure 94: Crack pattern and maximum load (kN) when cracks were observed in the compressive test (wall 2)

It is observed from the pictures and recorded video that there seemed to be a problem with the load distribution on wall 1, which in turn affected the creation of the cracks in it. The first crack was observed when 48 % of the total load was applied to the wall. Most cracks were seen on the left side, which confirmed that comparatively fewer loads were applied to the left side of the wall because the steel caps were not flat enough. However, for wall 2, a vertical crack started at the base wall when 68 % of the total load had been applied, which corresponds to a typical wall of low vertical stress for this type of wall (Varum et al., 2007). A similar cracking pattern was observed in a sun-dried brick wall under compression in Varum et al.'s (2007) study. Miccoli et al. (2016) tested two low walls with the following dimensions: a solid block wall with a size of (500 x 500 x 115) mm and a perforated block wall with a size of (500 x 500 x 175) mm. Similar perpendicular cracks were observed in these wall samples. This confirms the rigidity of wall 2 and the uniformity of the CEB and mortar strength to resist the horizontal load.

4.10 Conclusion

Three different earth elements (sun-dried brick, CEB, and CESB) were made, and a variety of experiments were conducted with the following conclusions being drawn:

- CSEB is not a favourable earth construction method for affordable housing since it consumed a large volume of Portland cement and did not provide a sufficient compressive strength.
- Considering the two other elements, CEB had a higher compressive strength, compared to the sun-dried brick, while both elements had a similar thermal conductivity. This made the CEB superior to the sun-dried brick for the construction of low-cost housing in Kabul.
- Deb-Sabz CEB had the highest compressive strength, 24 % higher than Arghandi and 31 % higher than Band-e-Ghazi, and it also had comparatively better resistance to water and abrasion than the other two CEBs. Therefore, it was selected for this study.
- For the non-stabilised earth element, the water absorption, measured by using a capillarity test (24 hours on the top of cotton or water absorbent paper), provided better results in comparison to direct contact with water. However, all the elements had little resistance to water and must be protected from running water.

- Elements made with Arghandi soil had the lowest thermal conductivity, which was 20 % lower than the elements made with Deh-Sabz soil.
- For the mortar, out of the nine mixes in the grid (see Fig. 87), mix design A with 1 kg of soil, 2 kg of sand, and 0.75 kg of water had the highest flexural-compressive strength and cohesion, thus being selected for this study.
- For the Deh-Sabz CEB and selected mortar, two wallets (slenderness 1 and 2) were made, and they were tested under compression. Even though the result was acceptable (2.59 and 3.1 MPa, respectively), it could have been better if the flat steel sheets had been used for the caps on both sides of the wallet during the test.

In this chapter, the best earth element (CEB) and mortar (mix design A) were selected for the construction of affordable housing in Kabul. The next chapter examines the optimisation of wall thickness and the creation of an architectural model for low-cost housing.

CHAPTER 5

OPTIMISATION OF WALL
THICKNESS FOR THE BUILDING
MODEL

CHAPTER 5: OPTIMISATION OF WALL THICKNESS FOR THE BUILDING MODEL

In the previous chapter, a series of analysis and experiments were completed, and as a result CEB was selected as the most responsive earthen element for the construction of affordable housing. Subsequent to this, mix design A was chosen as the most suitable for the mortar and interior plaster in view of the desirable model of housing. This chapter optimises the thermal performance of the surrounding walls and proposes the optimum wall thickness regarding the energy demands for the model house put forward in this thesis. This will enable the author to propose a comprehensive model of affordable housing that is responsive to the needs Afghan citizens living in Kabul, and thus which addresses the current housing shortage.

5.1. The software

To select the software for building energy simulations in this study, the results of a survey were used in determining the optimal software and the reasons why. A survey by Mohammad Rezvanpur (2018) from the University of Alberta was employed for these ends. In answer to this question ‘what is the best and most accurate software for energy simulation in buildings?’, he received 55 responses from academics and professionals (Rezvanpour, 2018). A small majority proposed the EnergyPlus software. His paper concluded that it is not only the software that affects the final results of a study, but it also the data input and the quality of the data and the availability and understanding of the software that are more important (Rezvanpour, 2018). In France, the ArchiWIZARD GRAITEC software has been used to simulate building energy (GRAITEC, 2022), and this software has also been taught in certain architectural schools. Hence, for this research, this software was selected, but it is not able to simulate wall surface temperatures, which are required for the optimisation of wall thickness. Therefore, the German software WUFI Pro (WUFI, 2022) was used for the wall surface temperature analysis. Further information and analysis will be provided below.

5.1.1. ArchiWIZARD software

ArchiWIZARD (GRAITEC, 2022) is a real-time 3D-analysis software based on the BIM model, which is directly connected to the architectural CAD solutions on a Mac and PC. ArchiWIZARD provides accurate thermal, light, solar gains and shadows analysis, and renewable energy simulation (for photovoltaic and thermal solar

systems). This software was designed for the optimisation and regulatory validation of building energy and environmental performance from sketch to the completion for both renovation and new constructions. It is simple to use, and it can be installed directly onto a computer or as a plug-in with Revit and ArchiCAD. The software has many good features that could be adapted perfectly for any project. It is in line with the French thermal regulations including RT2012, RE2020, EXISTING TR, EN 12831, and STD. This software is equipped with the EnergyPlus plug-in, and the results can be analysed and achieved in EnergyPlus as well. ArchiWIZARD is adaptable for any project in any location, but it requires the weather data file (epw) of that specific location.

For this study, Kabul epw was used, and the analysis was based on climatic data from Kabul. The software is equipped with a large library of various construction materials; further, it is possible to add material into it. This study employed the specifications of the Kabul soil and CEB analysed in Chapters 3 and 4. Thus, the simulation is based on that specific material. The model was prepared in Revit and transferred to ArchiWIZARD for thermal analysis. It was important to choose an epw which corresponds to the region where the project is located, so Kabul epw was selected (see Figs. 95 and 96). Then, the exact material and thicknesses for the walls, roof, and floor were applied, and finally a simulation was performed.

General information			
Habitable area (SHAB)		50.4 m ²	
SRT		76.6 m ²	
Volume		115.1 m ³	
Total heat loss area		179.0 m ²	
Heat loss area without floors		128.6 m ²	
Transfer area		244.2 m ²	
Indicators			
Compacity (A/V)		1.6	
Windows area ratio (A _{windows} /SHAB)		19.0 %	
Housing openings area/available facade area		12.3 %	
ψ ratio (ψ/SRT):		0.28 W/(m ² .K)	
Ubat		0.877 W/(m ² .K)	
Reference Ubat		0.556 W/(m ² .K)	
Walls	Area m ²	Thermal transmittance W/(m ² .K)	Thermal loss coefficient W/K
Lower floors	50.4	0.492	24.8
Roofs	50.4	0.728	36.7
Walls	68.6	0.857	58.8
Openings	9.6	1.598	15.3
Thermal bridges	Length m	Thermal transmittance W/(m.K)	Thermal loss coefficient W/K
Wall/wall junctions	98.9	0.208	20.6
Window/wall junctions	35.3	0.021	0.7
Thermal inertia class			
Individual housing		Very heavy	

Figure 95: Principal information for the model house, input data from ArchiWIZARD software

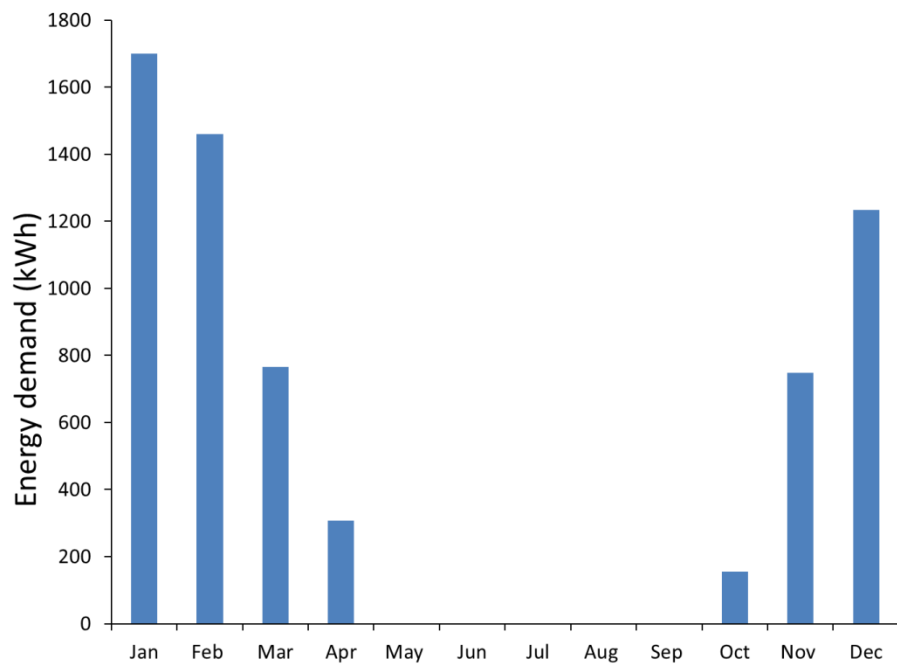


Figure 96: Monthly heating energy demand for the model house with a 505-mm wall thickness

5.1.2. WUFI Pro software

This software was designed by the Department of Hygrothermics at the Fraunhofer IBP, Holzkirchen in Germany (WUFI, 2022). It is a standard programme for accurately analysing heat and moisture transfer in walls and other multi-layer building components exposed to natural weather. The benefits of this software is that once the simulation is complete, the results can be interpreted with different codes (see Fig. 97), as shown below:

- a. EN 15026/DIN4108/WAT 6-2: hygrothermal performance of the building components and building elements, including an assessment of the moisture transfer by numerical simulation;
- b. EN ISO 13788: hygrothermal performance of building components and wall-interior surface temperatures to avoid critical surface moisture and condensation in the mass calculation methods; and
- c. ASHRAE 160: criteria for moisture-control design analysis in buildings.

For the calculation of the wall interior and exterior surface heat transfer, WUFI pro software was used, and the results are based on the ASHRAE standard (see Fig. 97). The Kabul climatic data (epw) and the heating set-point (19 °C) were also selected. The wall material specification changed according to the soil type that was analysed during this study (Deh-Sabz soil).

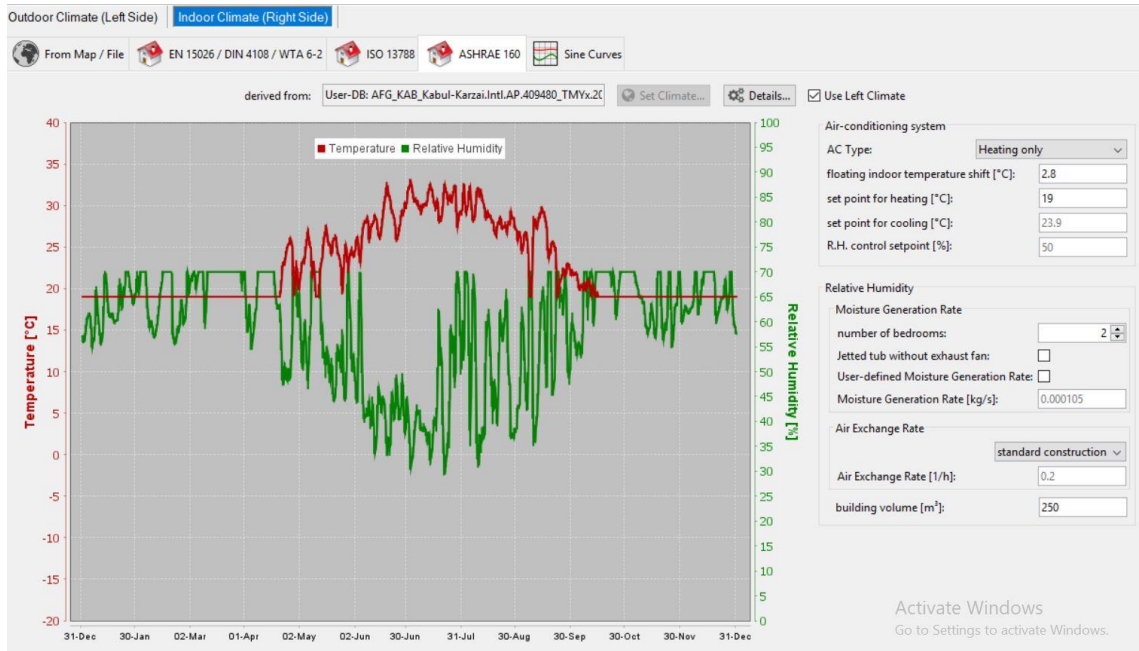


Figure 97: Indoor temperature and relative humidity simulation result for a 500-mm CEB wall, input data from WUFI Pro

5.2. Optimisation of the thermal performance of the wall

The heat storage capacity of the earthen elements has been well researched; however, the disadvantages in terms of insulation have been understudied (Yu et al., 2022). Moreover, there is some research that reviews the relations between the thermal mass and thermal properties of RE. A recent study on the optimisation of the thermal performance of the composite RE wall construction proposes a *comprehensive evaluation index method*. A design strategy for Beijing's cold climate in China was proposed, and a quantitative design strategy was developed for the wall thickness that is suitable for this city (Yu et al., 2022; Yu and Hao, 2022). This method is appropriate for earth-wall thickness optimisation; therefore, this research uses the same method to optimise the structural layer of the CEB. It also develops a quantitative design strategy for the wall thicknesses suitable for Kabul. The author hopes that this research is able to provide an applicable design strategy for both CEB and RE constructions that can be extended to other cold climate zones.

To ensure the validity of the evaluation index and uniformity of the sub-factors, the value of a certain type of index needs to be reversed through a steered inversion (Yu et al., 2022). Therefore, this method was used to perform the inverse index (U). This made all the sub-factors isotropic and was used to analyse the composite index values. Moreover, the mean value method was adapted for the dimensionless evaluation index

of the CEB walls, and this will enable the following: 1) to eliminate the adverse effects of the differences in the physical meaning; 2) to scale the units according to the results; and 3) to ensure comparability amongst the sub-factors (Yu et al., 2022). The aim is to balance the thermal performance and energy efficiency of the CEB wall and establish a comprehensive evaluation index of the thermal mass and insulation. In Chapters 3 and 4, the soil characteristics and CEB mechanical and thermal properties were analysed, and the results are used in this section to optimise the wall thickness. Four relevant metrics are considered: the heat transfer coefficient, thermal inertia index, temperature wave attenuation, and phase detention times. With the help of the ArchiWIZARD and WUFI Pro software, the relations between these relevant aspects are analysed, and a comprehensive multi-index evaluation method is established. This makes it possible to select the appropriate thicknesses for a new CEB wall construction. Kabul was also selected as it is a typical cold city in the cold region of Afghanistan.

5.3. Material properties

The selected soil taken from Kabul with an apparent dry density of $(1,594) \text{ kg/m}^3$ was wet-sieved and analysed, according to the ASTM (2006), and its particle-size distribution was determined (see Tab. 10). The result show that it is a silty clayed soil.

Soil particle size	Clay	Silt	Sand
Distribution (%)	27.6	70.4	2

Table 10: Soil particle-size distribution

The CEBs measuring $(290 \times 145 \times 100)$ mm using a manual hand-operated constant volume block machine were produced. All necessary physical properties of the block were determined, and the ISOMET Model 2104, heat transfer analyser, was used to evaluate the thermal performance of the block (see Tab. 11).

Name	Dry density ρ (kg/m^3)	Specific heat capacity c ($\text{kJ.kg}^{-1}.\text{K}^{-1}$)	Thermal conductivity λ ($\text{W.m}^{-1}.\text{K}^{-1}$)	Thermal storage conductivity S ($\text{W.m}^{-2}.\text{K}^{-1}$)
CEB	1,860	0.844	0.728	9.116

Table 11: Physical parameters of the block

5.4. Proposed model

Out of the three proposed affordable housing models explained in Chapter 6, model A was selected for further analyses. In model A, the left corner of the courtyard house was studied (see Fig. 98). This is because the houses located on the edge have relatively different sizes and one shared wall. The selected house covers a plot of 187.5 m^2 , out of which 82.5 m^2 is covered by the building and 4.5 m^2 by the pit-latrine. The

total courtyard wall length is 30.4 m. One wall of the building and two walls of the courtyard are shared with the neighbouring houses (see also Fig. 98). It is a south-oriented building where 38 to 64 % of the south wall is covered by openings to maximise the use of the winter sun, and the overhang prevents the sun from entering the building in summer.

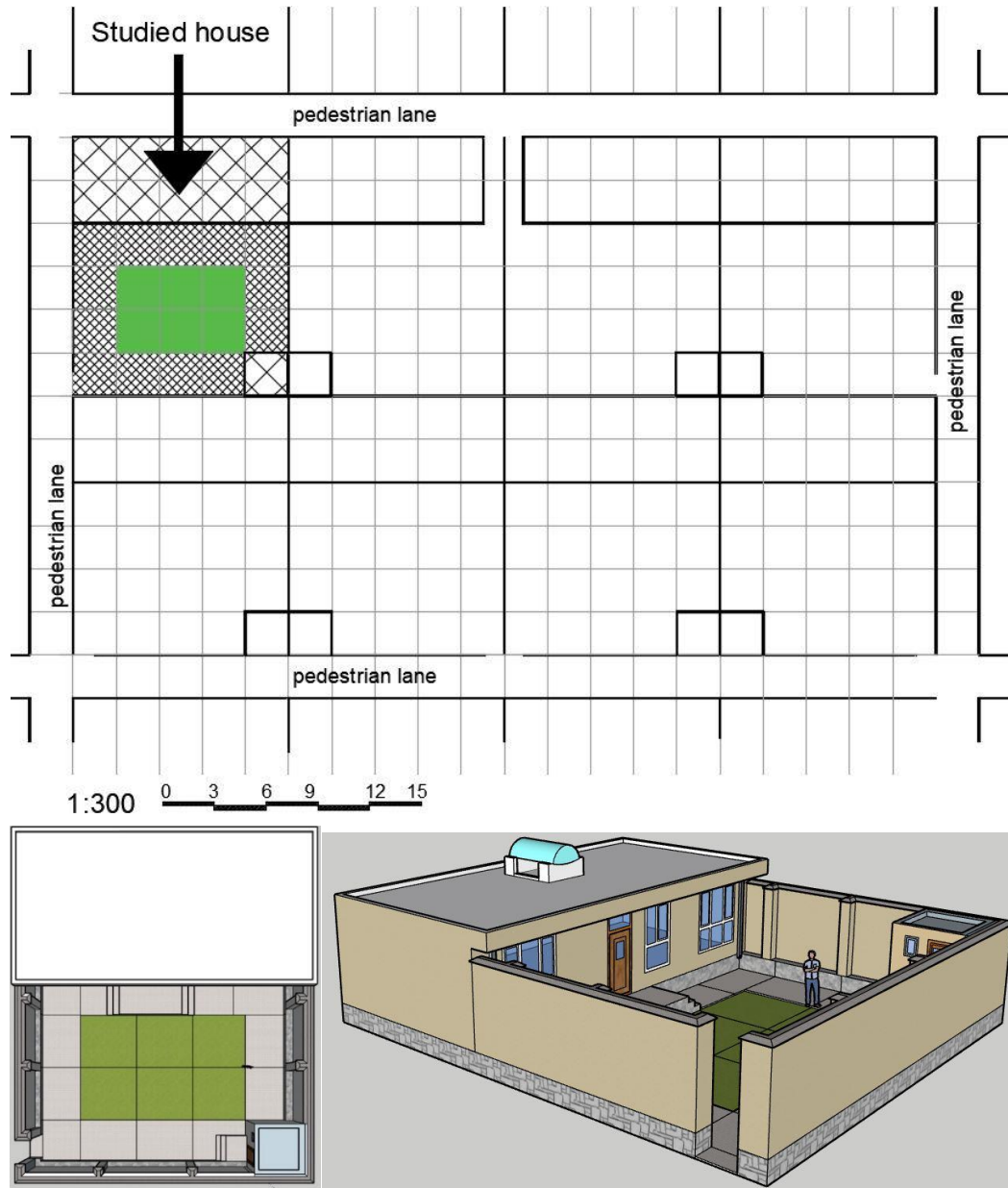
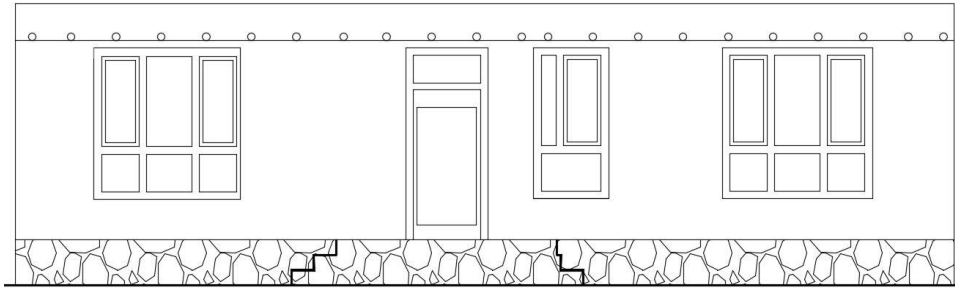


Figure 98: Location, top view, and 3D view of the studied house

The building contains two south-facing rooms, a kitchen, a bath, and a traditional pit-latrine (see Figs. 99, 100, 101, and 102). It is constructed on top of rigid stone foundations, with a light wooden structure (vertical and horizontal), which connects the foundations with the walls and the roof (see Fig. 103). A wooden lintel (150 x 150)

mm on the south wall and (50 x 50) mm rings on other walls level the top of the walls and provide a bed for the poplar woods and roof layers (see also Fig. 103).



South elevation

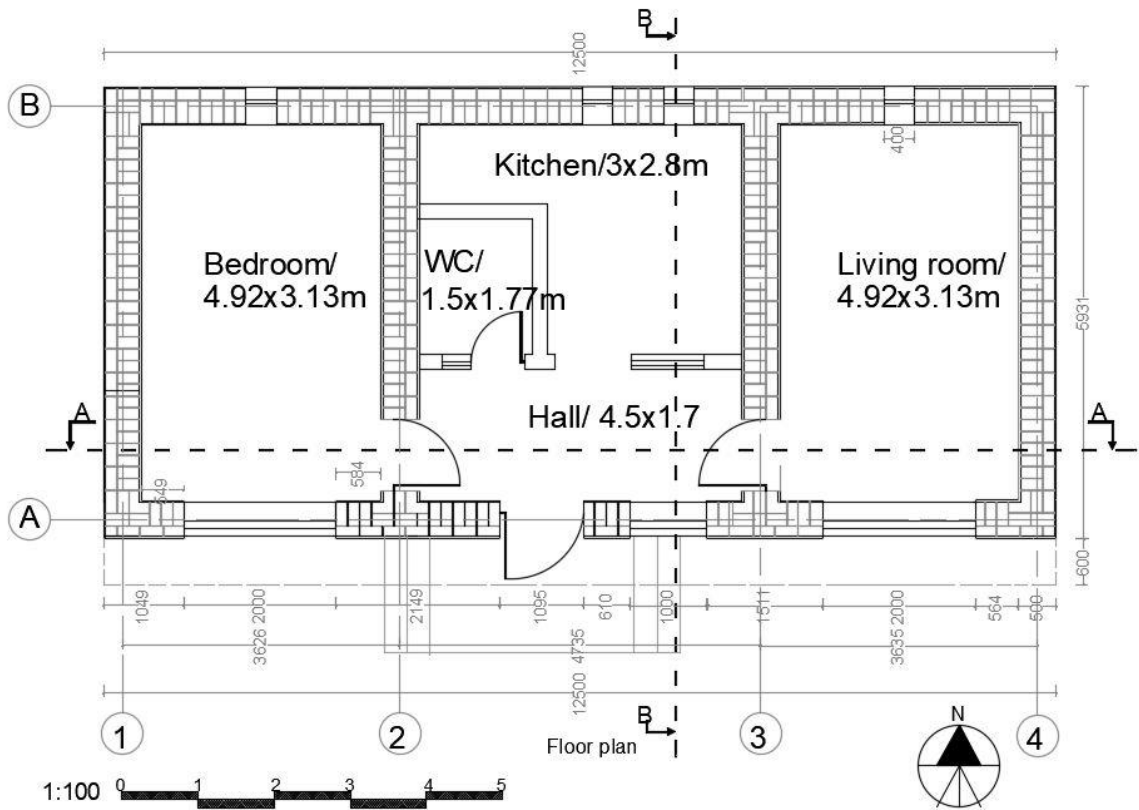


Figure 99: Proposed model plane and south elevation

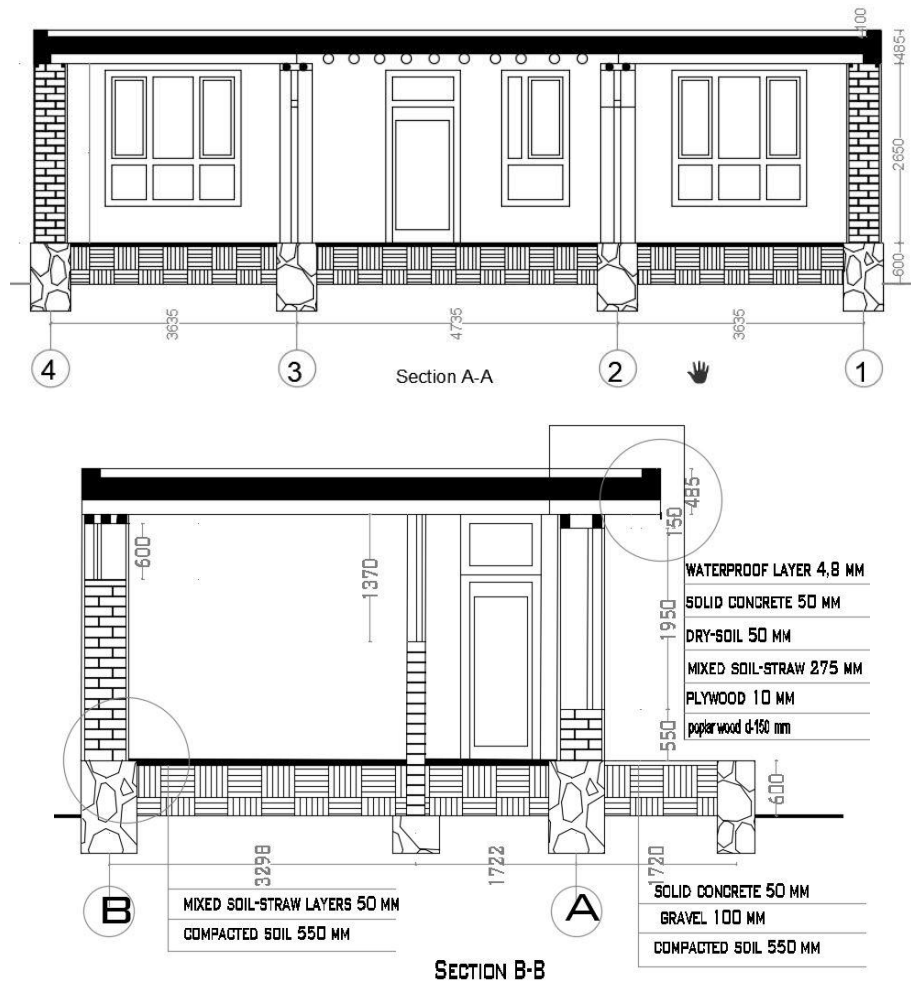


Figure 100: Proposed model cross-section

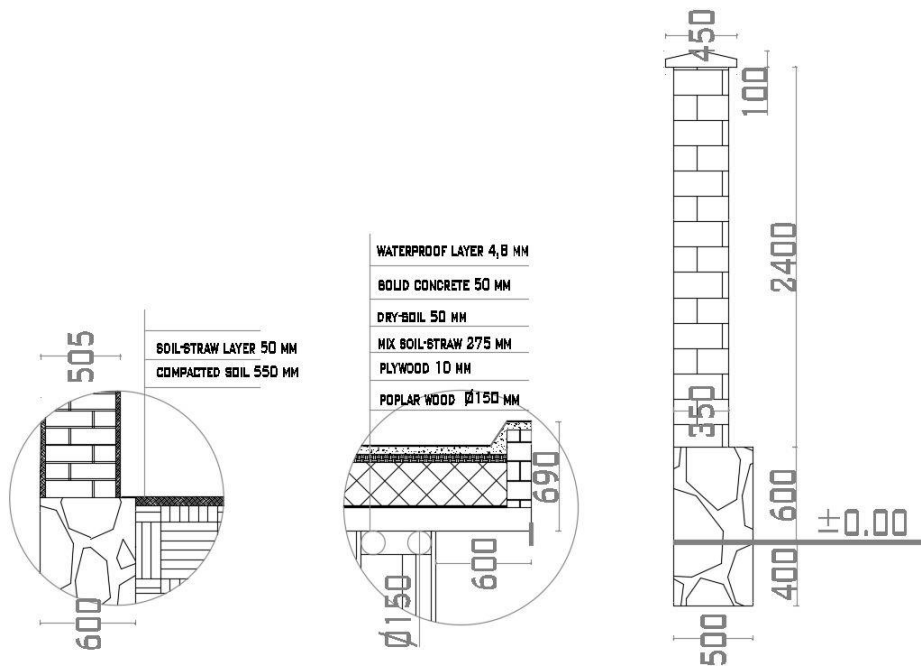


Figure 101: Proposed model foundation, roof, and courtyard wall detail-1:30

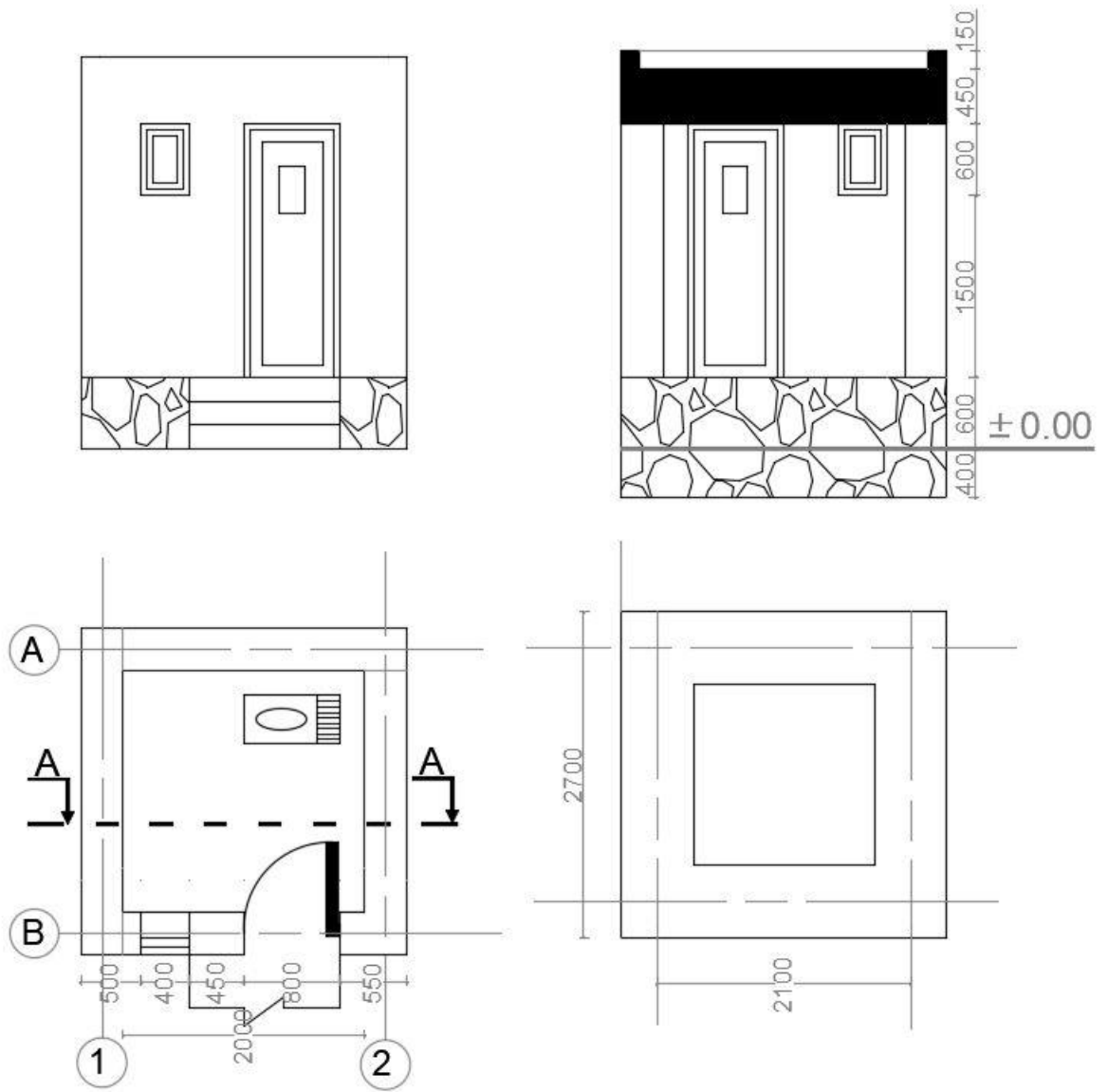


Figure 102: Proposed model with pit-latrine plan, elevation, and section

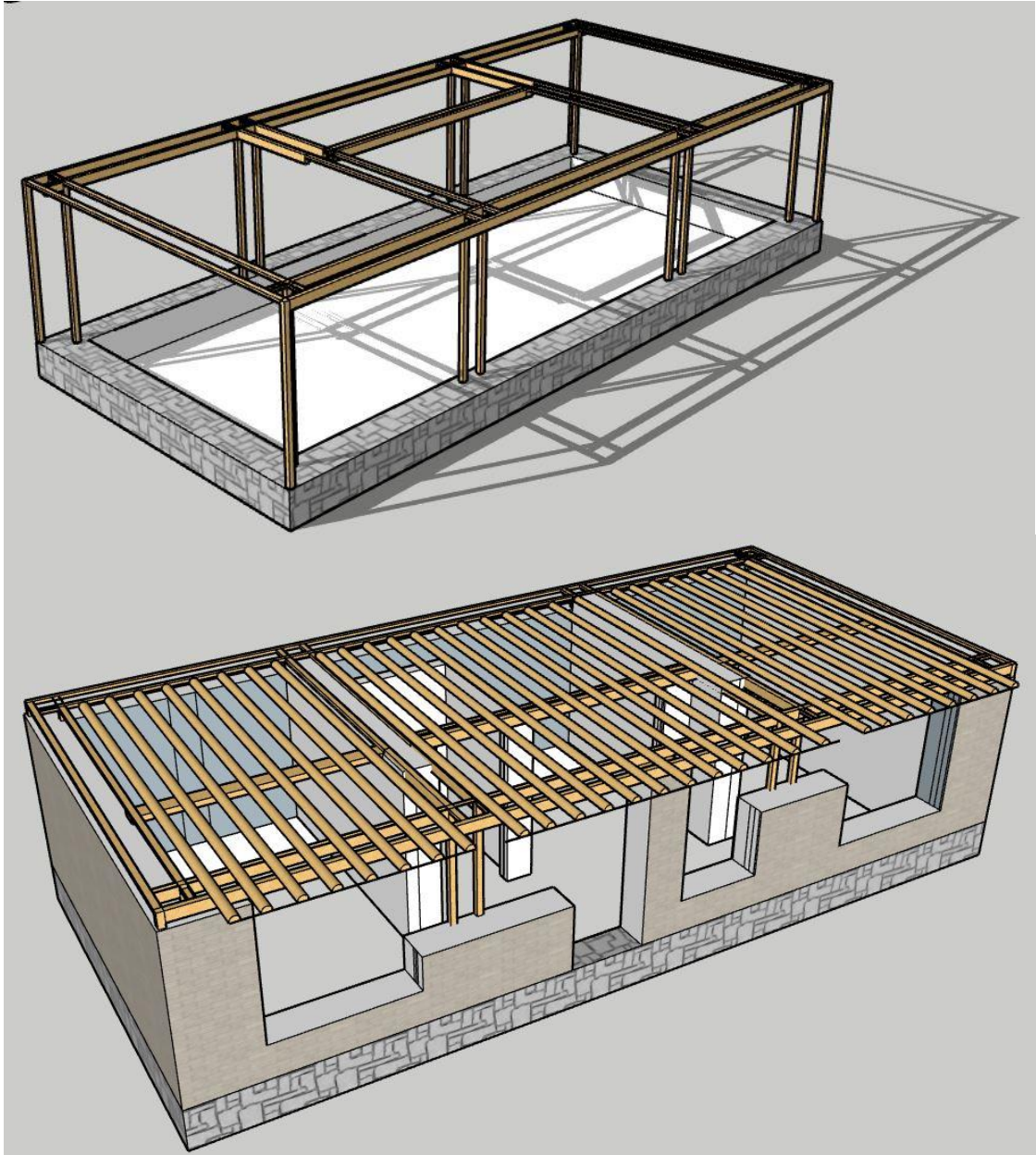


Figure 103: Proposed model stone foundation and wooden structure

5.5. Building prototype

To optimise the CEB wall thickness, an energy consumption model was established, and the impact of the different wall thicknesses (100-1000) mm on the building energy demand was analysed. The energy demand was analysed only for the heating of the house during the cold period, where in Kabul, it counts for 91 % of the housing energy demand. The east wall of the model is a shared wall with the neighbouring building, and thus the model has zero energy loss. It is a rectangular shape, on a single story, with one bedroom, one living room, one kitchen, and one bathroom. It is south-oriented with 600 mm of overhang to the south wall and a natural cross-ventilation system. The specifications of the model are summarised in Table 12.

Window-to-wall ratio (%)	South: 27.0	North: 2.8	East: 0.0	West: 0.0
Wall U-value (W/(m².K))	Varies with wall thickness			
Roof U-value (W/(m ² .K))	0.728			
Floor U-value (W/(m ² .K))	0.492			
Window U-value (W/(m².K))	1.598			
Heating set point (°C)	19			
Ventilation	Air ventilation			

Table 12: Specification of the model

5.6. Sub-factors

For evaluating the thermal performance of the CEB wall, two factors are commonly used: the thermal conductivity and heat storage capacity. The temperature (indoors and outdoors) and the constant state of the wall heat transfer will have a huge effect on the thermal conductivity; in other words, the greater the thermal conductivity of the wall, the more heat loss that occurs. However, the thermal storage capacity is the heat transfer caused by the outdoor environment. Fortunately, CEB has a good thermal storage capacity and the ability to absorb, store, and release heat. Yu et al. (2022) have converted the two factors into more detailed parameters (see Fig. 104), and they have shown the relationship (weak or strong) between these parameters and their influence on RE building performance. However, in this study, the same factors and parameters are used to analyse the thermal insulation and thermal mass that affect the CEB building performance, considering the physical properties of CEB and the outside climatic impact. Using the wall thickness as the only variable, a comprehensive evaluation index has been established following these parameters: heat transfer coefficient, thermal inertia index, attenuation degree, and phase detention time to evaluate the thermal performance of the CEB walls.

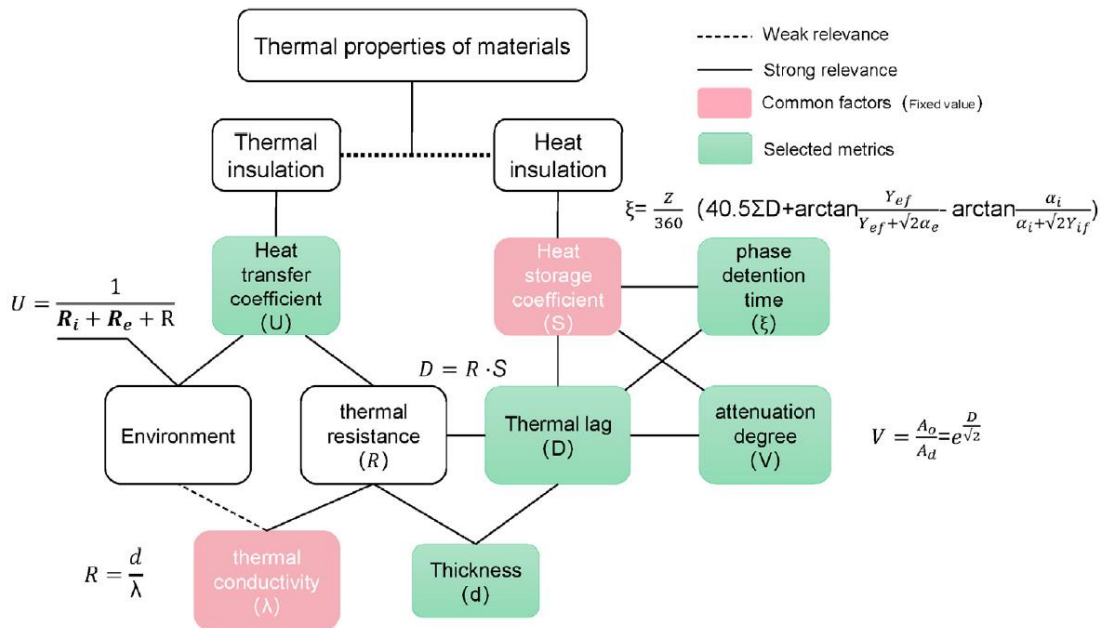


Figure 104: Relevance of the material's thermal parameters (Yu et al., 2022)

5.7. Analysis and calculations

As a general fact, when the wall thickness increases, the thermal insulation and thermal mass increase. However, it is not logical to blindly increase wall thickness in order to improve its insulation properties because this act decreases the usable space and makes the building vulnerable to seismic risk as CEB is a heavily weighted material. In this research, ArchiWIZARD was used to simulate the energy demand of the house, and WUFI Pro was used to dynamically analyse the heat and moisture transfer. Following to this, the parameters (heat transfer coefficient, thermal inertia index, attenuation degree, and phase detention time) were fitted to the varying wall thicknesses to analyse the optimum effective thickness of the CEB walls. It is worth mentioning that there are many formulas that have been used by Yu et al. (2022) and Yu and Hao (2022) for developing the comprehensive evaluation index method for the climate in Beijing. This study will use the same formula and relationships; however, the input data relate entirely to this research, and the climatic information in Kabul was used while running the simulations.

5.7. 1. Thickness and heat transfer coefficient

The WUFI Pro software was used to simulate the heat transfer coefficient of various thicknesses in the CEB walls, based on Kabul's regional climatic parameters. The heat transfer coefficient and thermal resistance of the walls were calculated (see Tab. 13). The thermal resistance was calculated using the $R=d/\lambda$ formula. The internal surface

heat transfer resistance ($R_i=0.125 \text{ m.K.W}^{-1}$), and the external surface heat transfer resistance ($R_e=0.0588 \text{ m.K.W}^{-1}$) were proposed by the WUFI Pro software. Therefore, the calculation was based on Equation 1 (Yu and Hao, 2022).

$$U=1/(R+R_i+R_e) \quad (1)$$

The heat transfer and conduction occur inside the walls which are influenced by the temperature and humidity of the environment. Looking from a microscopic perspective, convective heat transfer occurs inside the CEB wall under the action of the air and vapour pressure. Hence, the heat transfer coefficient is a numerical characteristic of convective heat transfer between the fluid and surface of the wall.

d mm	100	200	300	400	500	600	700	800	900	1,000
U (W.m⁻¹.K⁻¹)	2.826	1.946	1.462	1.185	0.986	0.851	0.744	0.664	0.597	0.545
1/U (m.K.W⁻¹)	0.353	0.513	0.683	0.843	1.013	1.173	1.343	1.503	1.673	1.833

Table 13: Relationship between the thickness and heat transfer coefficient

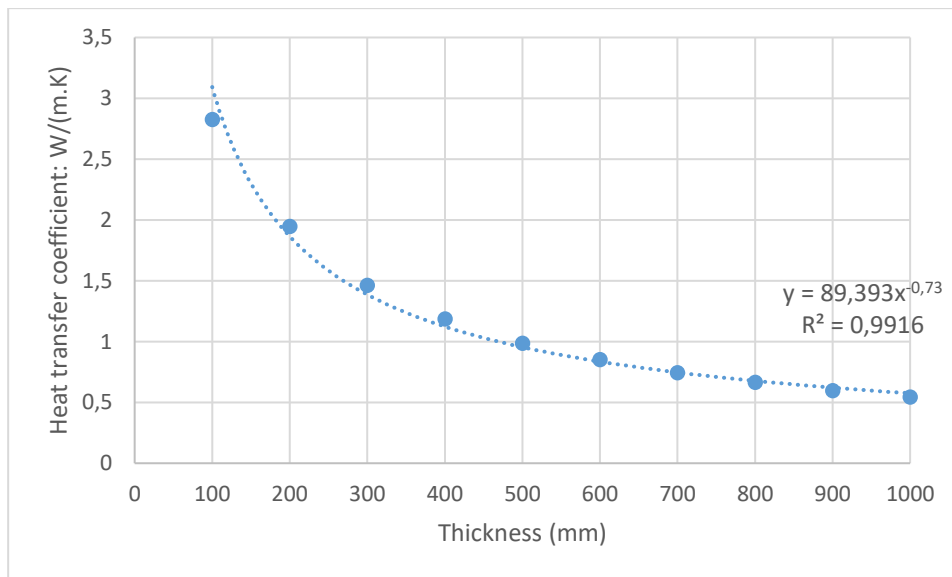


Figure 105: Fitting of the heat transfer coefficient

The analysis shows that with the increase in thickness, the heat transfer coefficient decreases, and the insulation performance of the CEB wall improves. Based on the above regression analyses and fitting the heat transfer coefficient to the wall thicknesses (see Fig. 105), $U= 89.4 d^{-0.73}$ was obtained, and the influencing factor of the heat transfer coefficient in the comprehensive evaluation index is $a_1=0.73$. The linear relationship after the dimensionless treatment of the thermal resistance is $\beta_1=0.0016$ (see Fig. 106).

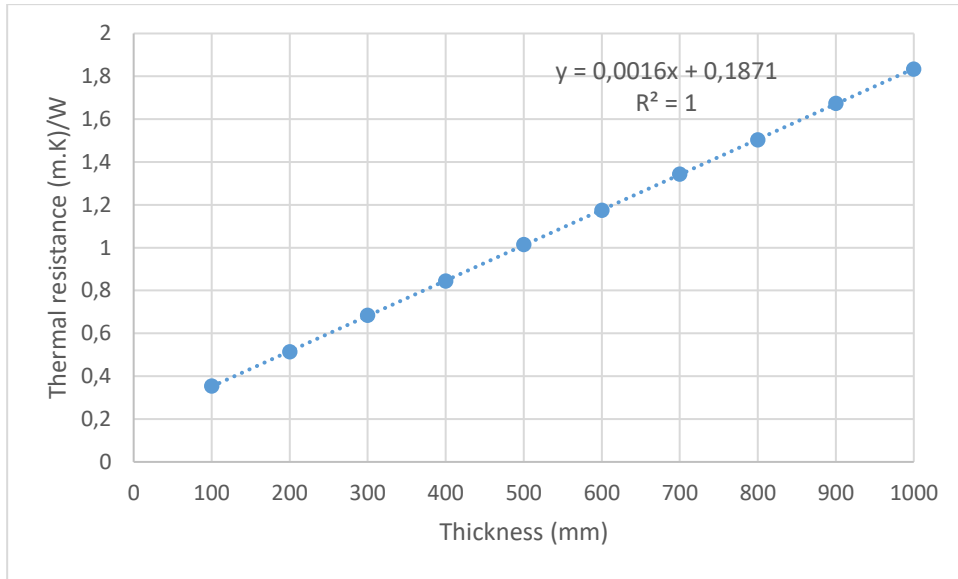


Figure 106: Fitting of the thermal resistance

5.7.2. Thickness and heat storage coefficient

The material heat storage coefficient depends on the specific heat capacity (c), density (ρ), and thermal conductivity (λ). 2π is a constant factor, and Z is considered for 24 hours (86,400 seconds) for Equation 2 (Yu and Hao, 2022).

$$S = \sqrt{\frac{2\pi c\rho\lambda}{Z}} \quad (2)$$

Since the effect of the wall thickness on the thermal storage performance cannot be accurately defined by only S , indicators related to the thermal performance of the walls were taken into account to assist the measurements in this thesis. The most directly related indicator to the thermal storage coefficient is thermal inertia, and with increases in wall thicknesses, it becomes larger. Moreover, a direct relation has been established between the temperature wave attenuation degree and phase detention time established and the wall thickness. By contrast, the two indirectly related indicators are attenuation degree and delay time. Moreover, the greater the thermal inertia of the wall, the better the performances of the indirect indicators.

5.7.3. Thickness and thermal inertia index (D)

D is a dimensionless index that reflects the rate of decline of the fluctuating heat transfer process of the external wall. The greater the D value is, the quicker the wall surface temperature is, and the better thermal stability of the wall. In Equation 3, the thermal inertia index of the CEB wall is equal to the heat storage coefficient multiplied by the thermal resistance (Yu and Hao, 2022).

$$D = RS \quad (3)$$

The thermal inertia index of the CEB walls with different thicknesses was calculated, and the fitting function is shown in Figure 107. It was found from the correlation of the function that the thermal inertia index of the walls is directly proportional to wall thickness, and the influencing factor in the comprehensive evaluation index is $a_2=1$, and the linear relationship is $\beta_2=0.015$ (see Fig.107).

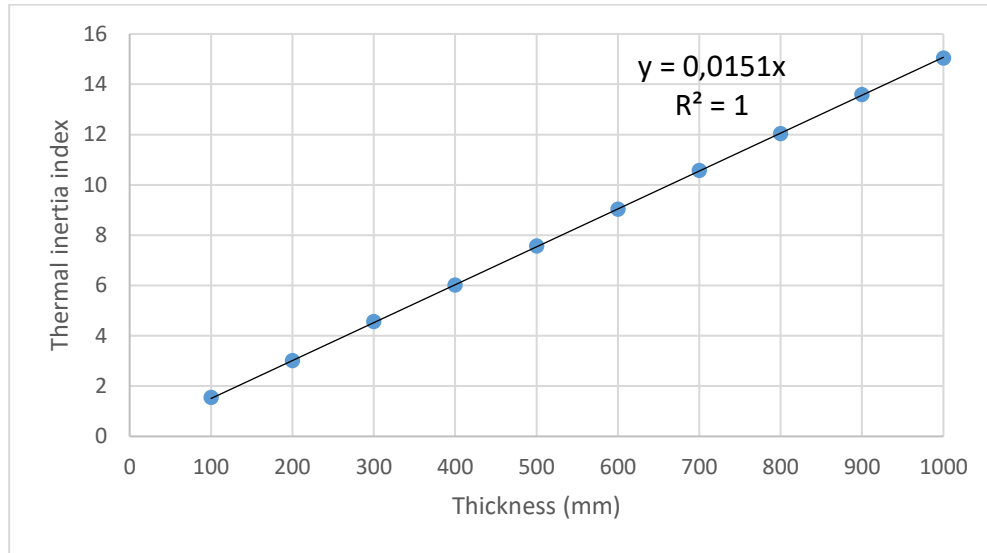


Figure 107: Thickness and thermal inertia index

5.7.4. Thickness and attenuation degree

The WUFI Pro was used to simulate the heat and moisture transfer process of the CEB walls with the different thicknesses. The outside climate conditions set by the software were taken from certain weather file (Kabul-hour.epw, 2022) and the interior ambient temperature was derived from the outside; however, the heating set point was manually set to 19 °C. The annual variation range of the internal and external surface temperature of the wall (100-1000 mm) thicknesses was obtained by the WUFI Pro simulation (see Tab. 14).

d mm	100	200	300	400	500	600	700	800	900	1,000
A₀ °c	42.7	43.3	43.7	43.9	44.1	44.2	44.3	44.3	44.4	44.5
A_d °c	24.4	19.2	16.9	15.7	15	14.5	14.1	13.8	13.6	13.4
V₀	1.75	2.25	2.58	2.9	2.94	3.04	3.14	3.21	3.26	3.32

Table 14: Thickness and attenuation degree

The value was defined as the average annual attenuation of the temperature wave (V_0) in Equation 4 (Yu and Hao, 2022). The ratio of the harmonic amplitudes of the internal and external surface temperatures was used to measure the attenuation effect of the CEB walls on the temperature wave (see Fig. 108).

$$V_0 = A_0/A_d \quad (4)$$

Where A_0 is the annual temperature amplitude of the external surface of the walls, A_d is the annual temperature amplitude of the internal surface of the wall (see Tab. 14 above).

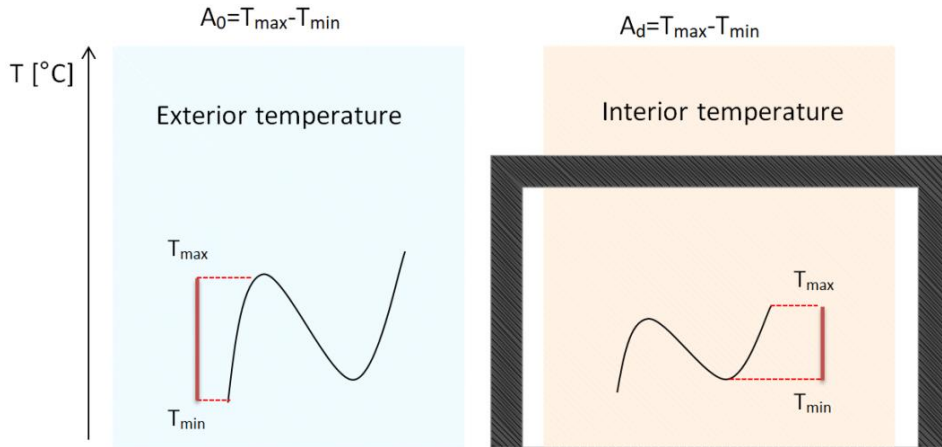


Figure 108: Minimum and maximum annual amplitudes of the interior and exterior surface temperature

With the increase in thickness, the wall exterior surface temperature increased weakly, and the interior temperature decreased. Therefore, it confirms that it is logical to keep this variation, rather than using one constant degree for the exterior surface, as it is the case for the two previous studies (Yu et al., 2022; Yu and Hao, 2022). Accordingly, these values were fitted with the wall thicknesses, and the results are shown in Figure 109. As the wall thickness increased, the attenuation degree increased, and the indoor temperature fluctuation and environment fluctuation range inside the wall became smaller. However, there is a growing trend of A_0 becoming smaller, and the increase in wall thickness reaching saturation for the attenuation gain. Based on the fitting function, the influencing factor for V_0 is $a_3=0.272$, and the correlation coefficient between attenuation and wall thickness is $R^2=0.974$.

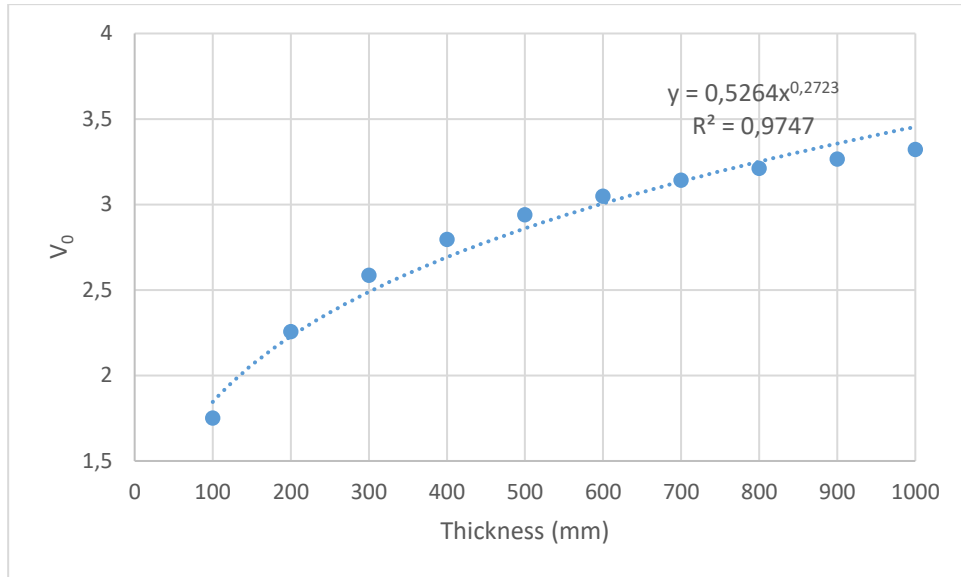


Figure 109: Fitting of the average annual attenuation of the temperature wave V_0

5.7.5. Thickness and time lag

The interval between the appearance of the peak outdoor temperature wave and the appearance of the peak indoor temperature of the exterior wall relates to the time lag (ξ). The greater the time lag, the less the impact of the outdoor temperature on the building's interior environment. The delay time for the various thicknesses in the CEB walls was calculated using Equation 5 (Yu and Hao, 2022).

$$\xi = \frac{Z}{360} (40.5 \sum D + \arctan \frac{Y_{ef}}{Y_{ef} + \sqrt{2x_e}} - \arctan \frac{x_i}{x_i + \sqrt{2Y_{if}}}) \quad (5)$$

Where Z is the time cycle, taking the value of 24 hours, D is the thermal inertia index of CEB; Y_{ef} is the heat storage coefficient of the external surface of the wall ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$); x_e is the heat transfer coefficient of the external surface of the wall ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$); and Y_{if} is the heat storage coefficient of the internal surface of the wall ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$). The power fit was performed (see Fig. 110). The calculation period is for 24 hours, and when the delay period was greater than 24 hours, it did not make sense to continue increasing the delay time for building the indoor environmental stability. The influencing factor of the time delay in the comprehensive evaluation index was calculated as $a_4=1$, and the linear relation was $\beta_4 = 0.04$ (see also Fig. 110).

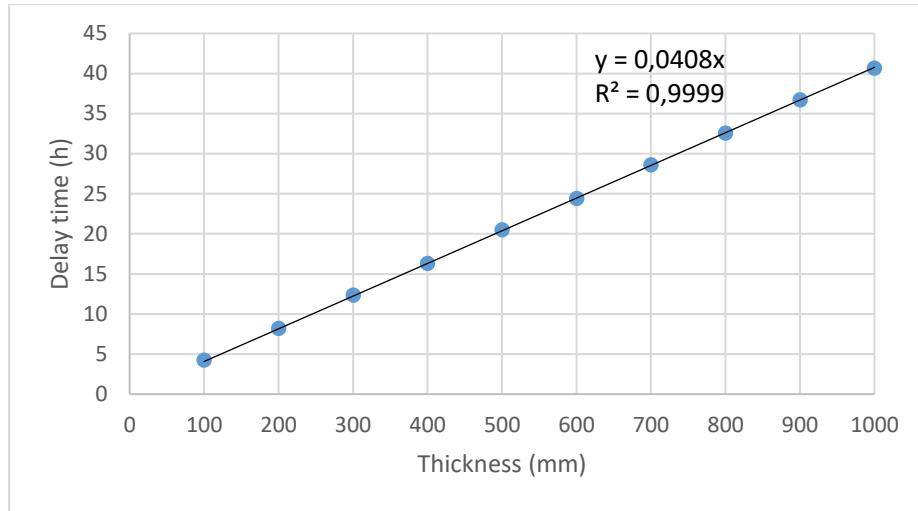


Figure 110: Linear fitting of the time lag

5.7.6. Thickness and comprehensive evaluation index

Based on the mentioned four-parameter influencing factors fitted above, the comprehensive evaluation factor (M) was established using Equation 6 (Yu and Hao, 2022). This factor was calculated for each wall thickness (see Fig. 111).

$$M = a_1\beta_1\frac{1}{U} + a_2\beta_2D + a_3V_0 + a_4\beta_4\xi \quad (6)$$

Where a_1 , a_2 , a_3 , and a_4 are the influencing factors of the four parameters, β_1 , β_2 , and β_4 are the linear relationships after the dimensionless treatment of each parameter.

The results show that as the wall thickness increased, the comprehensive evaluation index continued to increase.

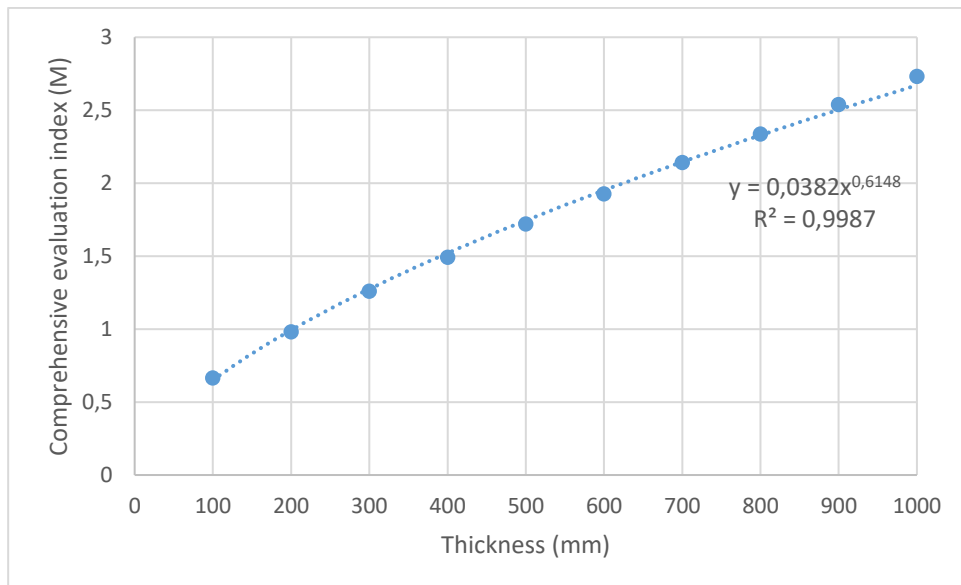


Figure 111: Relation between the thicknesses and M

5.8. Energy demand

The thermal performance of the CEB walls could be conceived by the energy demand of the building. Therefore, the CEB wall thickness as the only variable was used to study the building energy demand under various conditions. The effect of the CEB wall thicknesses (100-1000) mm on the energy demand was simulated using the ArchiWIZARD software (see Fig. 112). In Chapter 1, the comfort zone for residential housing in Kabul was selected to be between 19 and 26 °C, and thus the heating set point for the simulation was set to 19 °C. Then, the percentage of heat lost through the building envelopes, such as the roof, walls, openings, and floor, was analysed (see Fig. 113). The results showed that the vertical walls had the maximum energy loss (37) %, and then the roof, low flooring, thermal bridge, and the windows experienced a potential energy loss of (23, 16, 13, and 10) %, respectively. Windows are the main source of heat gain in the building through solar radiation.

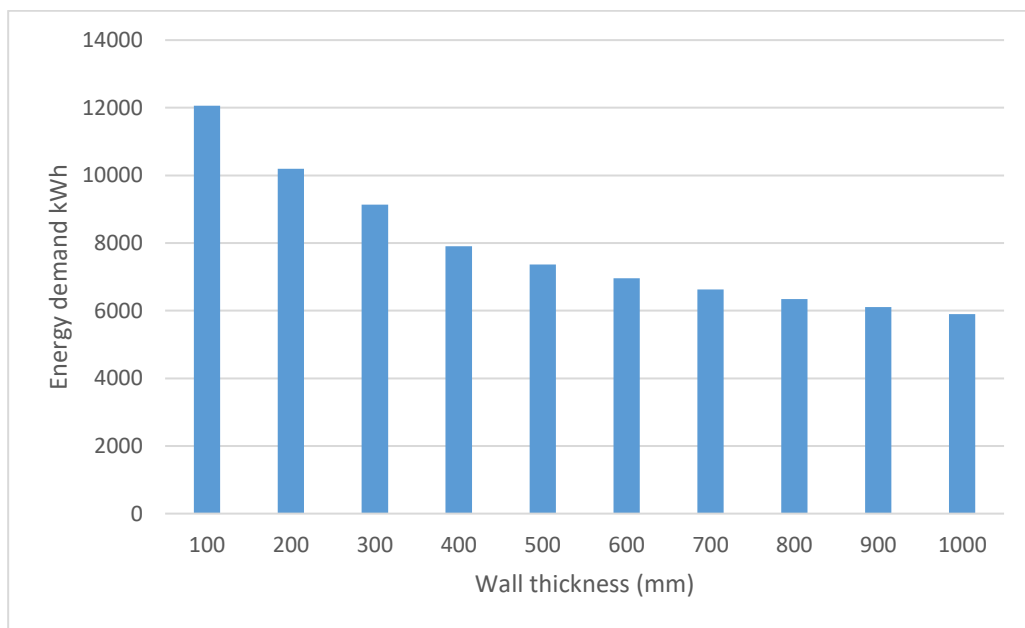


Figure 112: Yearly energy demand versus wall thickness

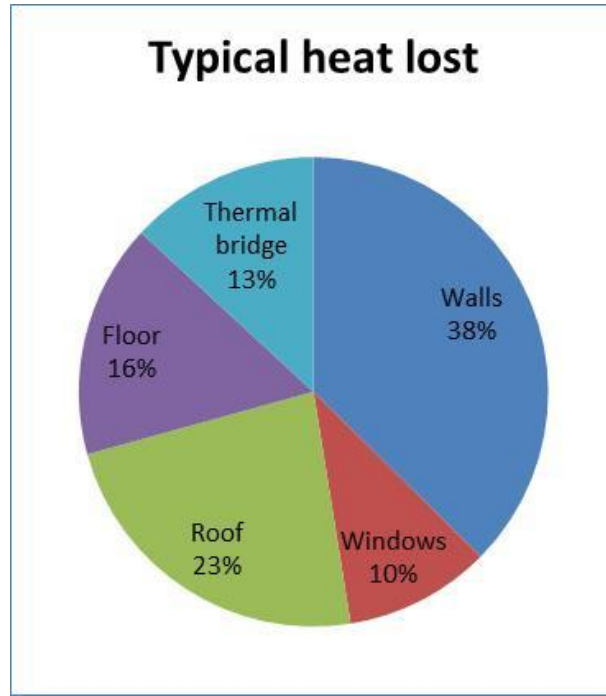


Figure 113: Typical heat loss in the model house

To find the relation between the energy saving rates and the thermal performance, two parameters were introduced. These are the energy consumption data (see Fig. 112), which were processed to achieve the energy saving rate for the walls (n_e), and the comprehensive evaluation index data (see Fig. 111), which was processed to find the thermal performance improvement rate (n_M); they were calculated using Equations 7 and 8 (Yu and Hao, 2022). The intersection between the two factors specified the optimum CEB wall thickness (see Fig. 114).

$$n_e = (E_n - E_{n+1}) / E_n \quad (7)$$

$$n_M = (M_n - M_1) / M_1 \quad (8)$$

Where E_n and E_{n+1} are the building energy consumption before and after gradient changes, respectively, M_n is the composite index after the performance improvement, and M_1 is the initial composite index. When $n_e > n_M$, the thermal performance improvement gain had a positive meaning; however, when $n_e < n_M$, the thermal performance improvement gain declined and had a negative meaning; further, when $n_e = n_M$, the thermal performance gain was at a maximum. Analysing the energy saving and thermal performance improvement rates of the walls made it feasible to select the optimum wall thickness marked in red in Figure 114.

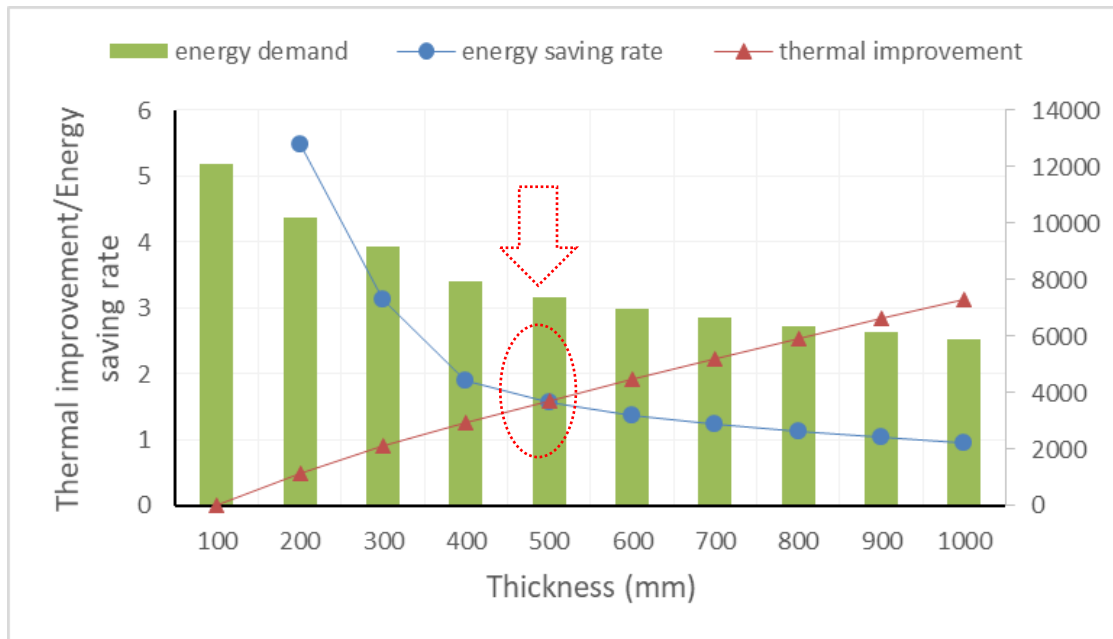


Figure 114: Energy saving rate, thermal improvement, and energy demand for the CEB walls

Performing the same procedure and analysis (Yu et al., 2022), the following results were achieved and conclusions drawn:

1. Energy saving rates and energy consumption gradually decreased with improvements in the thermal performance of the wall.
2. Energy saving rate and performance improvement reached a balance when the wall thickness reached 500 mm, achieving its best performance.
3. Considering the lower limits of the wall thickness, an optimisation was found, and the appropriate CEB wall thickness for Kabul is around 500 mm.
4. Considering this thickness, the proposed wall thickness consists of 1.5 CEB (435 mm), 10 mm of joint mortar, and 30 mm of soil-straw plaster on both sides of the wall, and the total wall thickness reached 505 mm. The arrangement of the CEB is shown in Figure 115.
5. The 30 mm of soil-straw plaster with lower thermal conductivity improved the heat transmittance of the wall from $0.978 \text{ W.m}^{-2}.\text{K}^{-1}$ to $0.857 \text{ W.m}^{-2}.\text{K}^{-1}$. This also reduced the annual heating energy demand of the building from 7,894 kWh for 500 mm of CEB wall to 6,377 kWh for 505 mm of composite wall. In addition, the plaster is able to protect the wall from rain and environmental impact.
6. If a further interior insulation layer (50 mm of thick soil-straw panel boards) is applied to the model house, an extra 4 % energy will be saved annually.

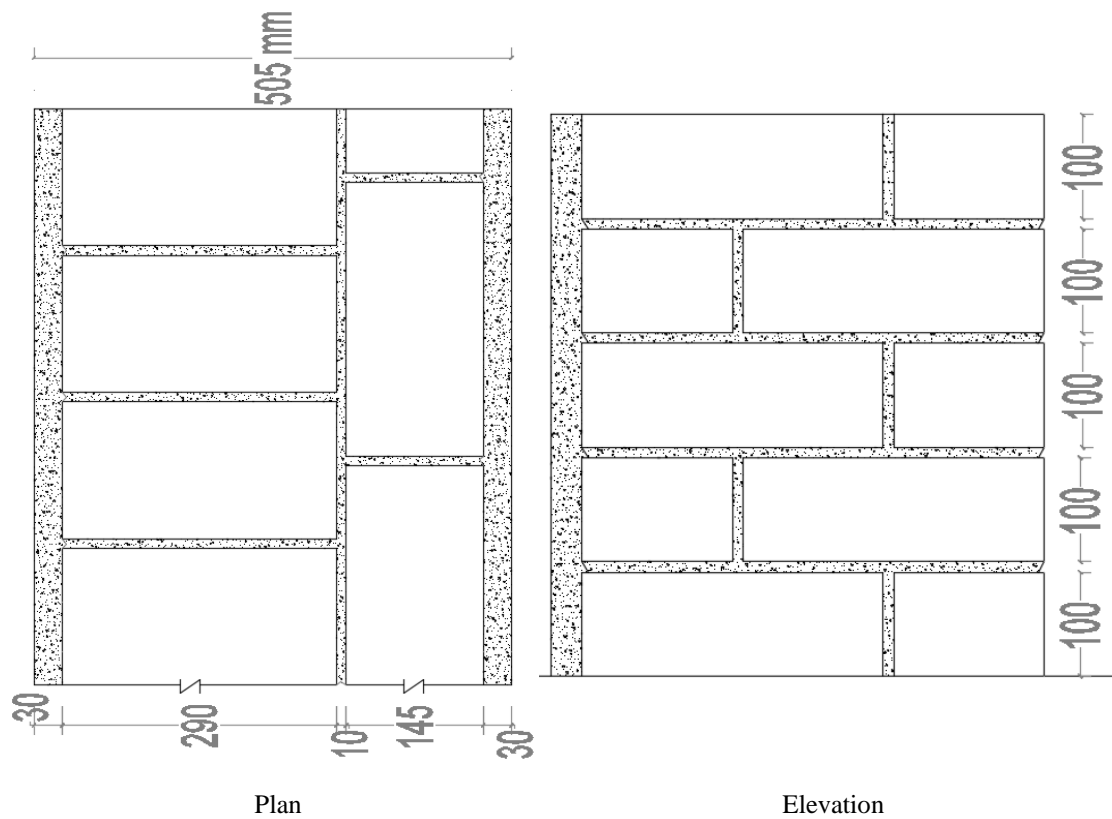


Figure 115: CEB arrangement in the plan and elevation

5.9. Conclusion

In this chapter, all the necessary calculations on the selected model were carried out. The thickness of the wall was optimised based on the thermal performance of the walls. It was found that with the increase in wall thickness, the thermal insulation and thermal mass increased. After a simulation of the energy, heat, and moisture transfer, the four parameters (heat transfer coefficient, thermal inertia index, attenuation degree, and phase detention time) were fitted to the varying wall thicknesses, and the optimum CEB wall thickness was found. Then, a model for the affordable housing programme in Kabul was proposed, and detailed drawings were discussed. In the next chapter, the cost calculations and design concept for the model are discussed. The existing models in Afghanistan and the three proposed prototype models for Kabul's affordable housing are also further discussed.

CHAPTER 6

PRELIMINARY TYPOLOGY AND
ARCHITECTURAL DESIGN OF THE
BUILDING MODEL

CHAPTER 6: PRELIMINARY TYPOLOGY AND ARCHITECTURAL DESIGN OF THE BUILDING MODEL

Chapter 5 focuses on the thermal performance of the walls, and after a series of analyses, the optimum wall thickness was determined. Based on these calculations, a model house was proposed, and its heating energy demand was analysed. To balance the thermal performance and energy efficiency of the CEB walls and establish a comprehensive evaluation index of the thermal mass and insulation, a set of procedures were used. There is a lack of literature on the optimisation of CEB wall thicknesses; therefore, this study lays the groundwork for future studies in this area, potentially providing a guide to building constructors. In this chapter, existing social housing models, housing morphologies, and layouts are discussed. A design concept has also developed, based on which three prototype models for an affordable housing programme in Kabul are further proposed.

6.1. Existing models

Currently, three prototype models for affordable housing construction exist (UN-Habitat, 2017): one for Kabul (incremental housing); another for Herat; and finally a global model for all urban areas in Afghanistan. However, to date, these models remain theoretical since they have not been practically applied. It is important to mention that there was another low-cost housing model applied in Morocco during the 1960s (Saaid and Chaoui, 2020), the idea of grid system applied for the residential housing is of interest to this thesis.

In view of these existing models, UN-Habitat (2017) proposed three types of low-cost housing units for Herat (see Fig. 116). Sample pilot units were built with rammed earth (RE) (Model 1), an interlocking mud block (Model 2), and a concrete block (Model 3). The units have simple plans (see Fig. 117), and they were built on the top of a stone foundation with a reinforced concrete ring. The roofs were constructed with 1 beam and filled with fired brick, locally called Taaq. They are detached, one-room houses, with a kitchen, bathroom, and a traditional pit-latrines (see also Fig. 118). It was impossible to gain access to all the detailed drawings, but access was granted for one plan and its associated images (UN-Habitat, (2017)). From the exterior, Model 1 was plastered with thatch, Model 2 was built without plaster, and Model 3 was plastered with a sand-cement combined mortar. The roofs were insulated with a plastic sheet to prevent water penetration and to keep the roof dry during the spring and winter seasons.

Unfortunately, these models were not applied practically in Herat, and with the fall of republic government to the Taliban, it was difficult to complete this project. However, a sample building from each type was built, and the costs of the buildings are summarised in Table 15 below. The data referenced here was derived from personnel communications with UN-Habitat staff working for the UN before the collapse of the republic government in Afghanistan. The French architect Lashermes Naik and Abdul Raqib Ekleel, doctoral student and town planner, are the two that helped me with these data.



Figure 116: From left to right: units made with concrete block, interlocking block, and RE (UN-Habitat, 2017)

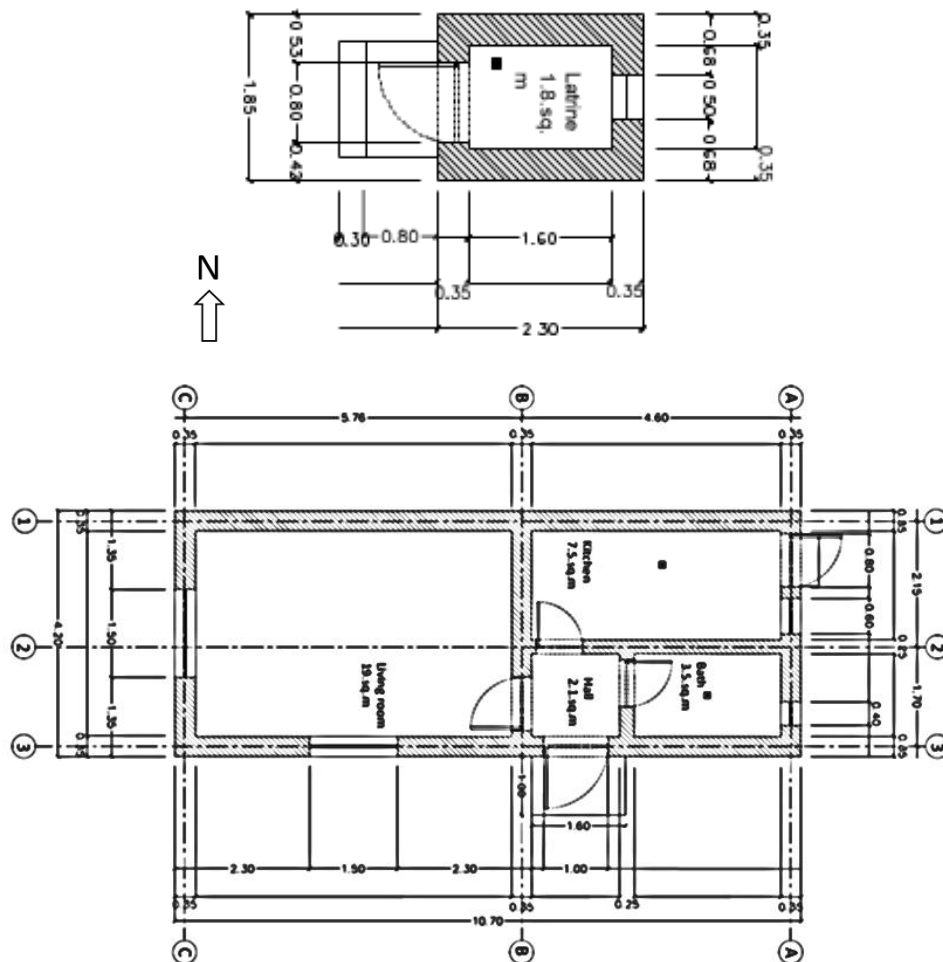


Figure 117: Low-cost housing unit building and pit-latrine plan (UN- Habitat, 2017)

UN-Habitat models	Total cost \$: house + latrine	Floor area: house + latrine	Cost in \$/m²: house + latrine
Model 1 RE	6,360	58.8	109.12
Model 2 Mud block	4,526	//	77.66
Model 3 Concrete block	5,492	//	94.23

Table 15: Cost per m2 of models (UN-Habitat, 2017)

The cost analyses showed that the interlocking mud-block houses were cheaper in contrast to the RE and concrete block ones. This is interesting for this research and confirms that the use of CEB is the best material for a low-cost housing programme. The UN-Habitat model building covers a relatively large area, but it has only one room, thus proving difficult to accommodate a large Afghan family, where the average family size is 6.5 per familial unit (UN-Habitat, 2017). Moreover, it is difficult to extend the building and add an extra room to it as it is not considered during the design of the building. The surrounding walls are neither thick nor insulated, so there is a chance of substantial energy loss, which increases the total energy demand of the building; hence, it would be helpful to improve this design before practically applying it for an affordable housing programme in Herat. More importantly, the cost per m² is high, which is mainly due to the use of reinforced concrete beams over the foundation and walls.

The second type of low-cost housing proposed by the Ministry of Urban Development and Land (MUDL, 2018) is called incremental housing. At the Ministry, a descriptive presentation was prepared about this type of housing, which included the needs for such housing, typology, plot areas, drawings, materials, and cost analyses (MUDL, 2018). This guide was prepared based on the 305th decree of the former republic's President Mohammad Ashraf Ghani to build low-cost housing for migrants (internal and external), those with disabilities, and for families of former military who died in service. It is called incremental because the house is designed to be built in four stages, based on household need. During the first stage, the design stipulates a plot of 250 m², a living room, kitchen, bathroom, pit-latrine, and courtyard to be built for a family (see Fig. 118). Subsequently, the household would be able to gradually add an extra room(s), if necessary, and even build another floor on top of the building. MUDL (2018) proposed three types of local materials for the construction of this low-cost housing: pakhsa (Model 4), stone (Model 5), and fired brick (Model 6). They houses were proposed in two forms: detached and semi-detached (see Fig. 119). The thickness of the walls were indicated only for Model 6 (350 mm) in the presentation.



Figure 118: From top: models of incremental housing, using pakhsa, stone, and fired brick (MUDL, 2018)

Note: Since the thickness of the wall for the pakhsa and stone models was not clear in the presentation, only one plan is presented. Similarly, the thickness of the courtyard wall was not determined.

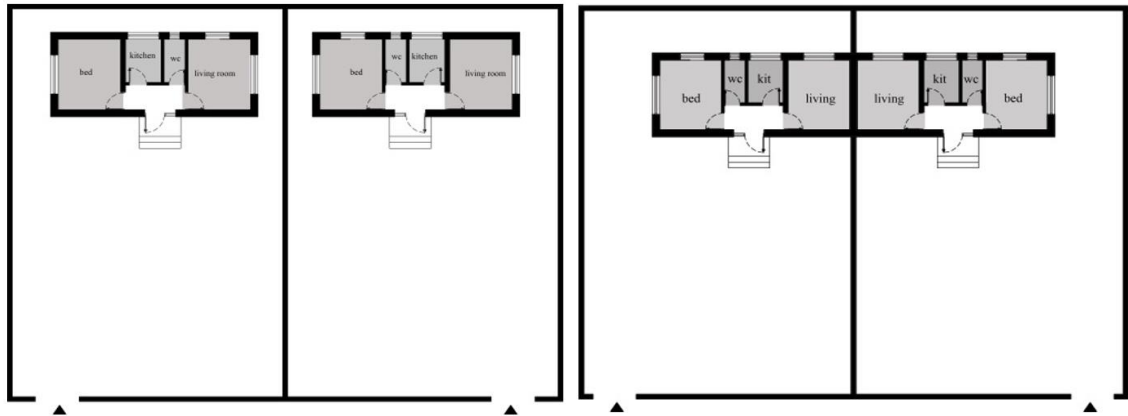


Figure 119: Incremental housing: detached and semi-detached (MUDL, 2018)

MUDL models	Total cost \$: building	Floor area: building	m ² cost in \$
Model 4 pakhsa	2,755	50.1	54.9
Model 5 stone	3,250	50.1	64.8
Model 6 fired brick	2,990	42.7	70

Table 16: Cost breakdown of the models at the first stage, without pit-latrine and boundary wall (MUDL, 2018)

For the MUDL (2018) models, a detailed cost breakdown was not available; however, the cost/m² was relatively inexpensive when compared to the cost of the UN-Habitat (2017) models. An analysis of the four models is given below:

Model 4: A heavy reinforced concrete ring above the openings does not seem logical, and it would be difficult for the pakhsa wall to tolerate this load. In addition, depending on the time of the year, a layer of pakhsa wall takes 3-to-5 days to dry and to tolerate the second layer; this long duration would be more pronounced if this model were to be applied for mass-housing construction.

Model 5: The stone masonry walls would require more space, work, and money, compared to the brick and pakhsa. A large amount of sand and lime mortar would be required for building the stone walls and also the reinforced concrete beam on top of the walls; it is not environmentally friendly and seems not suitable for Kabul.

Model 6: The cost/m² of burnt brick is relatively more expensive than for sun-dried brick and pakhsa. Fired brick requires energy to prepare and transport it to the construction site; hence, this would use more embodied energy, which is not good for the environment.

Above all, these models are not thermally optimised, and the thickness of the walls and roof layer is not clearly stated in the presentation, so it is important to have a detailed design and thermal optimisation of the models before applying them.

The third model was proposed by Kazimee (2006), a professor at the Architectural School in Washington State University. He claimed that a cluster of residential courtyard houses with a semi-private space and shared walls could save up to 50 % in energy and would be affordable for many Afghans. In this contemporary approach for low-cost housing, Kazimee (2006) defines the private space for each house and also the semi-private space where the women could meet each other and have parties (see Fig. 120). He argues that the cluster-type housing could preserve the identity of the traditional housing fabric and would be compatible with the Afghan lifestyle. Extended families could share social amenities, culture, spaces, and live together as a small community (Kazimee, 2006).

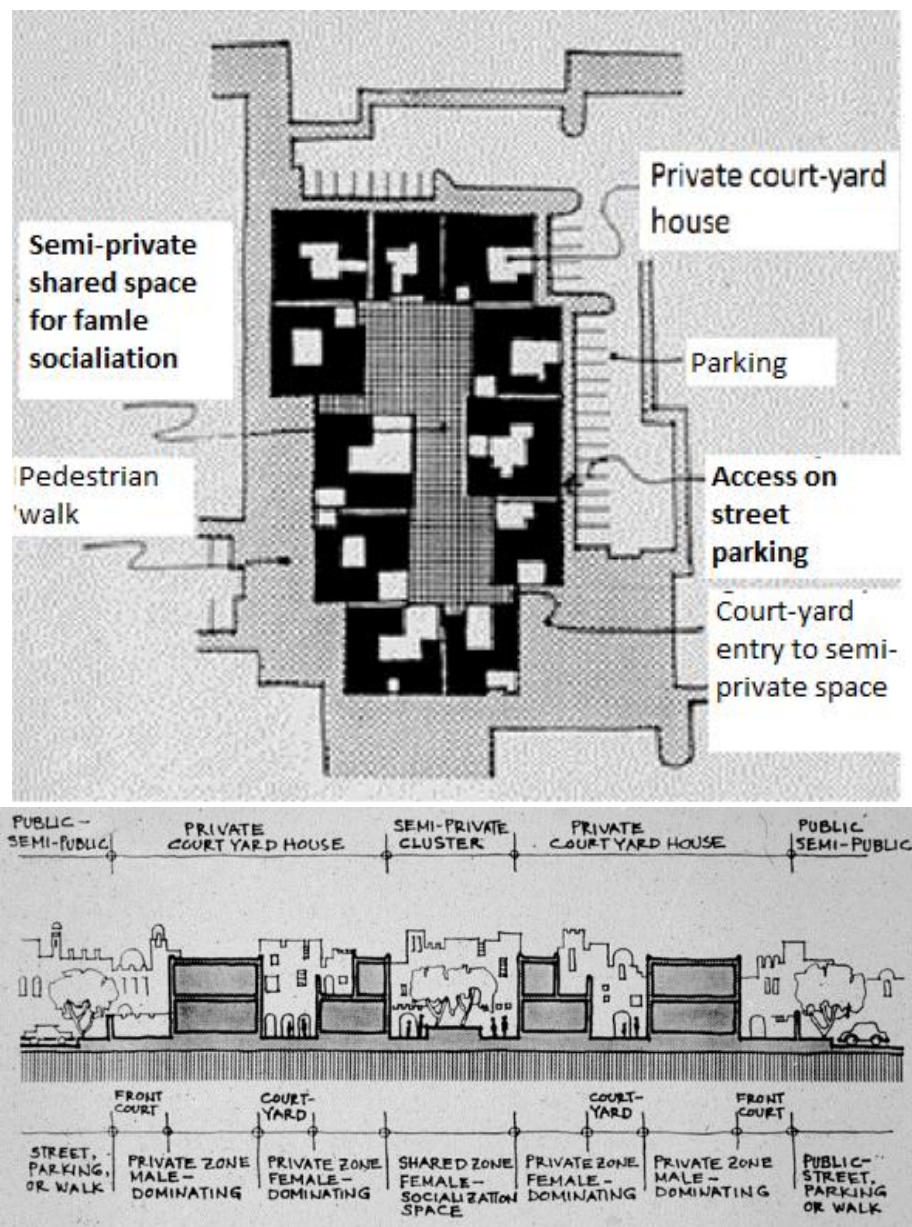


Figure 120: Plan and cross-section of a cluster courtyard houses with semi-private spaces (Kazimee, 2006)

Another model for low-cost housing was proposed for Casablanca, Morocco. In 1953, the grid system was introduced for Casablanca to address the urgent need of housing in the ninth International Congress of Modern Architects (CIAM) in Aix-en-Provence, France, (Saaïd and Chaoui 2020). In the 1950s, to find an answer to the problem of housing for the rural migrants who came to the city, the French urbanism services led by Michel Ecochard proposed patio grid housing in terms of meeting local cultural needs. Every patio (courtyard) house was to be covered 8 x 8 m; this included the building and patio. A unit of four houses were to be connected with a 2.4-m wide lane, and the cars were not allowed to enter the houses (see Fig. 121). Every house was to have a tiny patio, two or three rooms, and a separate kitchen and bathroom. The widths of the main streets that connected the units were 8 m, which complied with the grading system (Saaïd and Chaoui 2020).

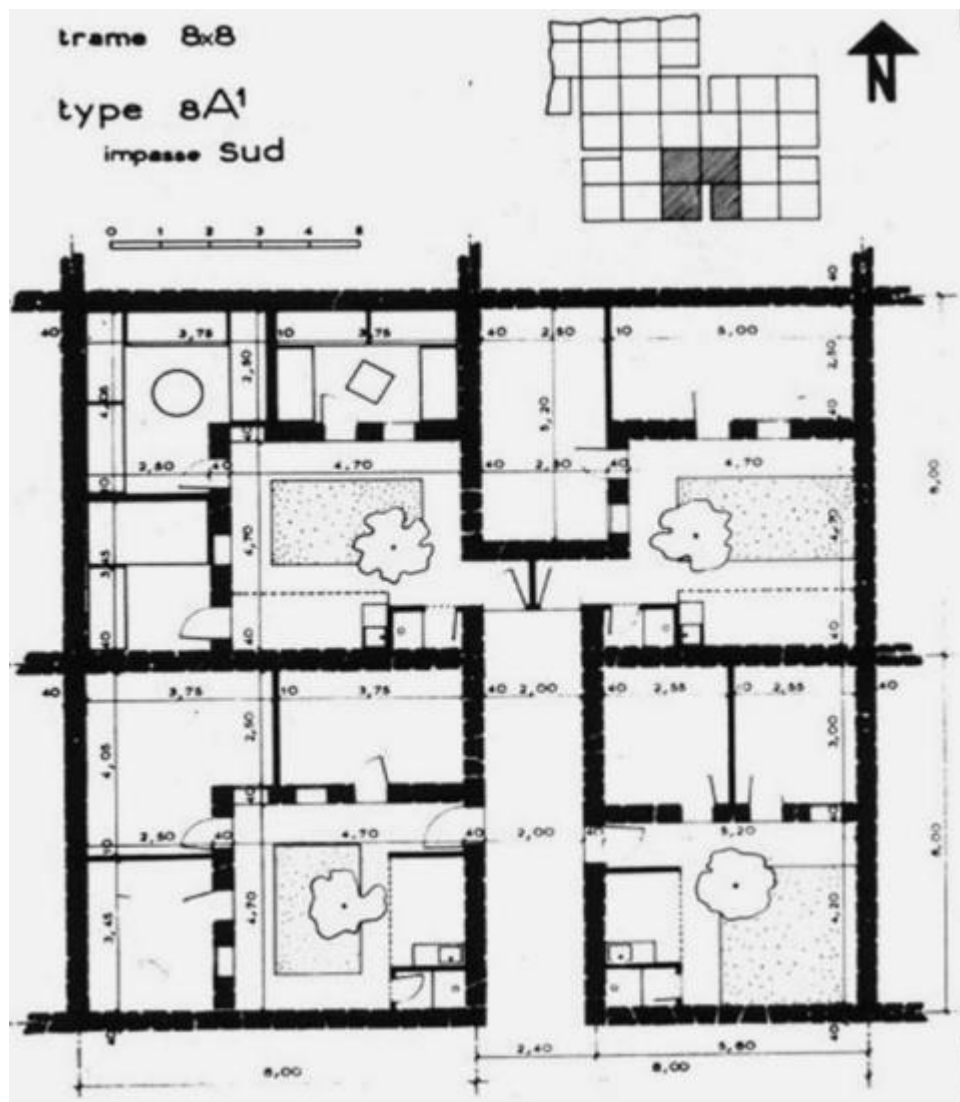


Figure 121: Casablanca: grouping of four 8 x 8 units with 2-to-3 rooms (Saaïd and Chaoui, 2020)

The houses were designed to have small patios, which were responsive to Morocco's hot climate, but they are not applicable to Kabul. This is because for Kabul, a bi-climatic design is necessary, with a larger courtyard to the south of the building to benefit from the winter sun. However, the idea of grading is interesting and has been applied to the low-cost housing models proposed for Kabul.

6.2. Design morphology

To meet all the challenges and propose an optimum design morphology for an affordable housing programme in Kabul, the existing housing models have been extensively examined. Amongst the different housing types, such as courtyards, apartments, and Qalas, courtyards constitute part of the typical urban fabric since they are able to accommodate large extended families, thus addressing the problem of high-population density (Kazimee, 2006). Unfortunately, the housing that has been built has, on the whole, been unplanned, on flat land, hillsides, or mountains, in various parts of Kabul. The models proposed in this thesis, however meet the desires of the people and seem to be culturally responsive to the citizen needs. This thesis selects the same housing type and adds to this by proposing a sustainable and affordable model, which constitutes a simple design, which is spacious and takes advantage of a shared wall(s) to reduce total energy demands.

In Kabul, there are two types of courtyards with different morphologies used: traditional and modern (Sharifzai et al., 2016). Many examples of the first type exist in Kabul's old city, the eighteenth century Murad Khani pedestrianised area is a good example (Hakim-Ebrahim and Devillers, 2022); currently, this community provides housing for forty-two households, most of which accommodate more than one family, and with a total of 523 people living there (TMF, 2016). The houses are connected with tiny pedestrian lanes laid east and west, which prevent cars from entering into the residential area. Depending on the house, the rooms are located to the south, east, west, and north.

Figure 122 shows the famous types of building location within a courtyard for both traditional and modern courtyard housing. In traditional houses, usually one or two attached walls are shared with neighbours (lot 1), which improves energy saving through high thermal mass and a shared envelop. However, there is problem with the building orientation, the south-facing rooms gain maximum benefit from the sun, and they have longer hours of comfort during the winter, and the overhangs prevent the sun from entering rooms during the summer period (Hosham, 2019), while the north-facing

rooms never see the sunlight. Similarly, rooms are located in the east and west parts of the courtyard (lot 1). The morning and afternoon sun can irritate some of the residents, especially during the summer period.

However, the modern type of courtyard houses have wider streets, and the rooms are mainly located in the north of the courtyard (south-facing), with wider gates, allowing cars to enter the courtyards. They are well-oriented to the Kabul climate, mostly because the main rooms are south-facing (see Fig. 122; lot 2). However, they are principally detached houses with walkways on two, three, or four sides of the building and do not benefit from the shared walls.

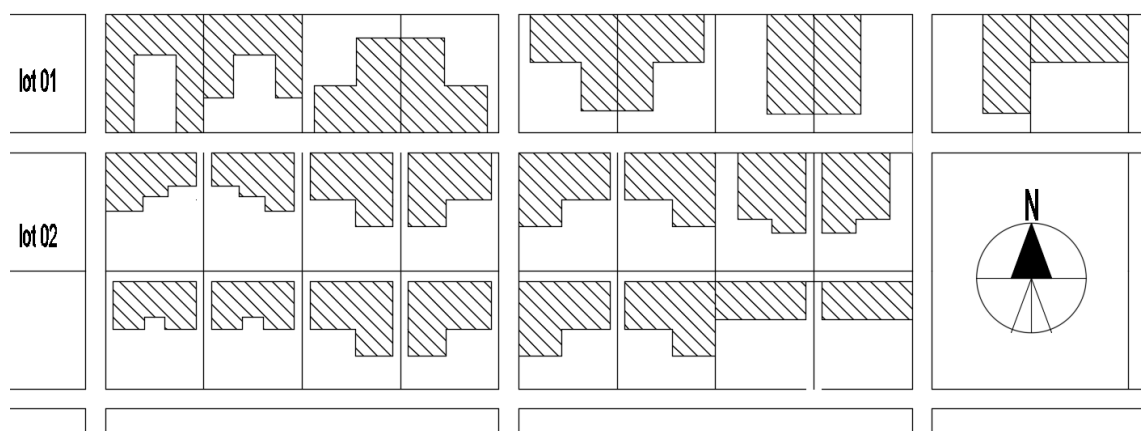


Figure 122: Existing morphology for courtyard houses

The proposed morphology for the affordable housing takes advantage of the traditional-modern courtyard houses and the grid system. A pedestrian scale design could be a desired morphology for the low-cost housing in Kabul, which will maximise land-use, which is an issue in Kabul, comply with the traditional architecture, and affect the total cost of the house. Three prototype models (A, B, and C) have been designed during this study (see Fig. 123). Two types of courtyard have been designed: a small-sized one (187.5 m²) with two rooms; and a medium-sized one (218.75 m²) with three rooms. What makes these models novel is the application of a grid system, with grids of 2.5 x 2.5 (6.25 m²) linking the private space, building, and courtyard with the public space by horizontal and vertical lanes. Similarly, the width of the pedestrian lanes (2.5 m) follows the grid system. The proposed low-cost housing is a global model that could be applied in any part of the city and its districts, where land for low-cost housing will be allocated.

During this study, it is not the aim to design a complete area, rather three lots have been designed with a proposed layout and morphology, including the building connections to nearby lanes (see Fig. 123). Units of eight houses have been designed together, where each house has one or two shared walls. To minimise the land use, encourage traditional culture, and pedestrianised areas, private cars are not allowed to enter the houses; however, in emergency situations, ambulances and small vans will be able to reach the entrance of each courtyard. Regarding the fire-brigade, the urban planners will provide a better solution, while applying the model in Kabul. Therefore, while applying the proposed model for low-cost housing, collective car parks must be considered within the residential area. Detailed information about each model is provided later in the prototypical model design, section 6.4.

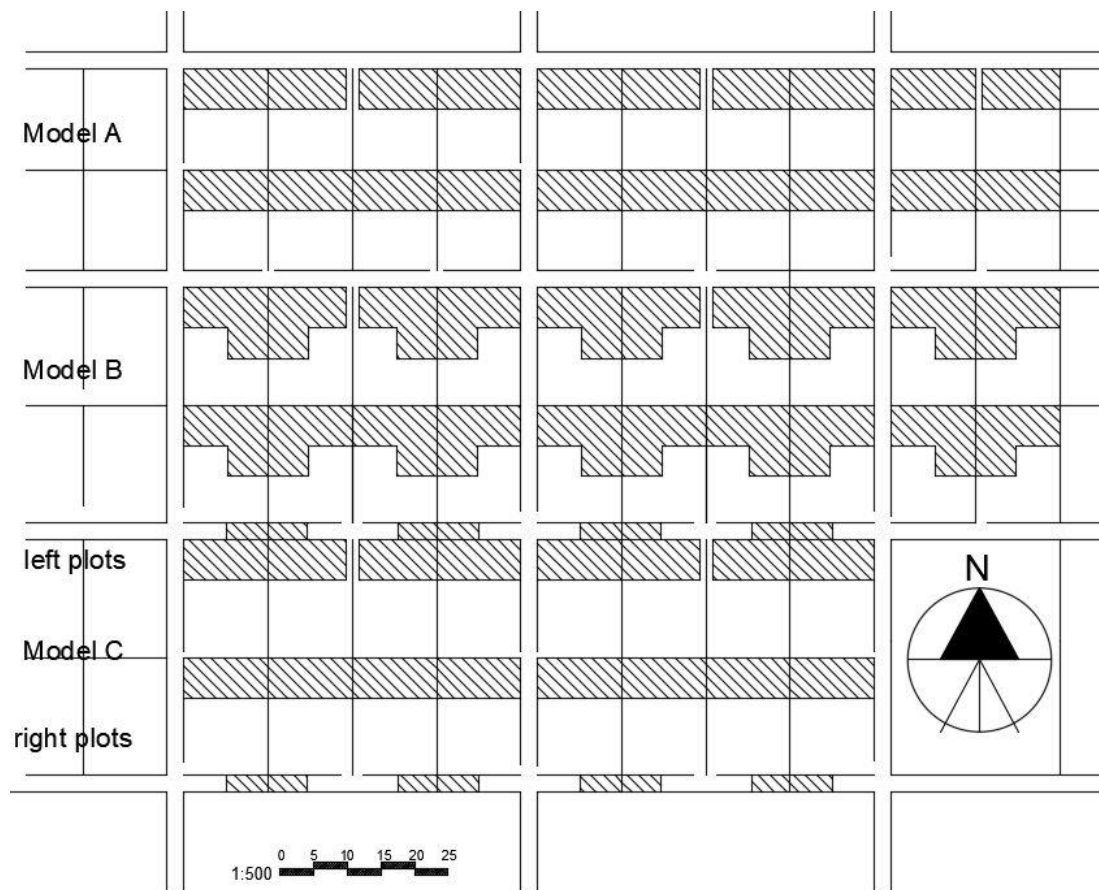


Figure 123: Proposed morphology for Kabul's affordable housing programme

6.3 Building layout

The majority of the residential buildings in Kabul are courtyard houses. Within the courtyard, households can add extra rooms according to their needs. Therefore, it is not easy to find a uniform building layout in traditional courtyard houses (see Fig. 124). However, in modern courtyard houses, as previously mentioned, the orientation of the

rooms is important, as illustrated in Figure 125. Moreover, the apartments have a global conventional block layout as seen in any part of the world. Two to three blocks can be located in the same building, and they are accessible through separate halls and staircases. Depending on the family size, two-, three-, four-, and five room apartments are available in Kabul. A good example is the prefabricated blocks made with the Soviet Union's assistance during the 1960s (see Fig. 126).

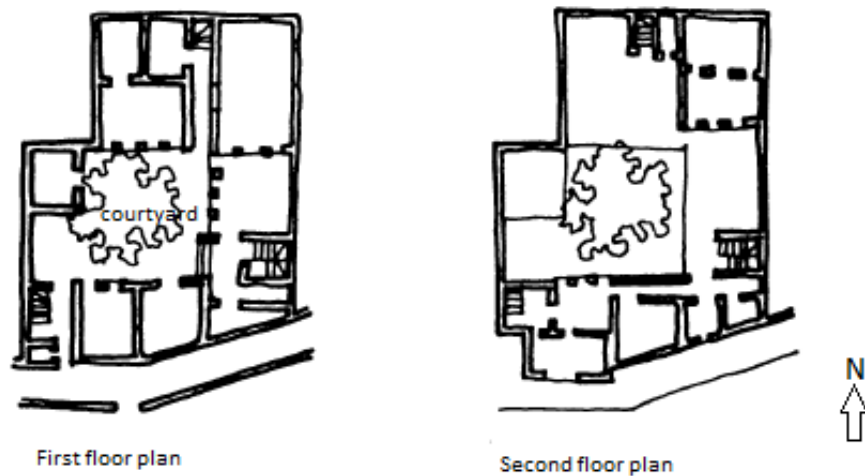


Figure 124: Traditional courtyard house building layout in the old city of Kabul, Shor Bazaar (Samizay, 1974)

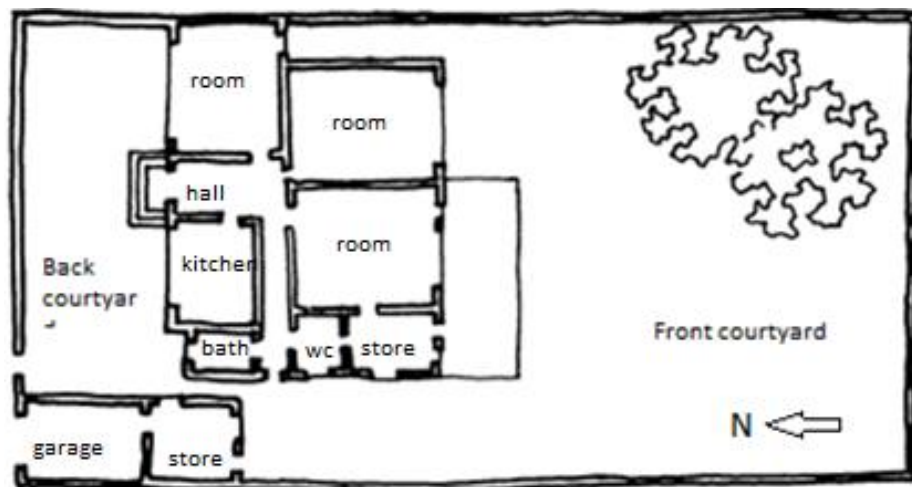


Figure 125: Modern courtyard house building layout in Kabul, Shar-e-Naow (Samizay, 1974)

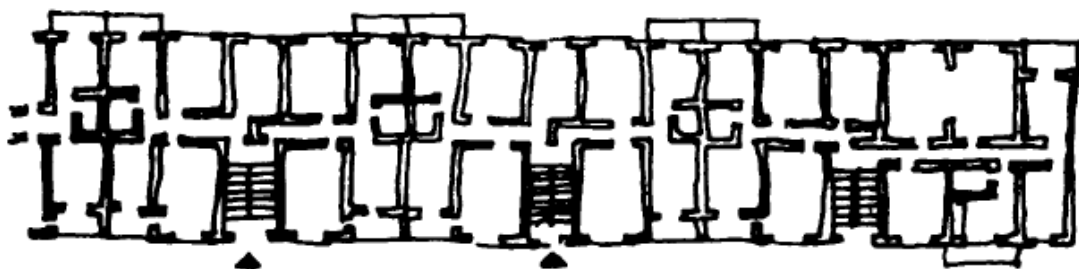


Figure 126: Prefabricated block layout, microrayan (Samizay, 1974)

For the affordable housing programme in Kabul, there is a need for effective use of land, maximum use of local materials, labour, a passive design strategy, and less energy demand. The two layouts have already been introduced for the low-cost housing by the UN-Habitat (2017) and by the Ministry of Urban Development and Land (MUDL, 2018). In this section, the proposed prototype models and layout will be discussed in detail.

6.4. The prototypical model of design

In this study, three responsive models for the affordable housing programme for Kabul are proposed: 1. A simple rectangular-shaped building with two rooms and a small courtyard (**Model A**); 2. an L-shaped building with three rooms and a medium-sized courtyard (**Model B**); and 3. a two-floored, rectangular-shaped building with four rooms, and one extra room that covers the pedestrian lane with a medium-sized courtyard (**Model C**).

These models and complete layouts are shown below, and they all will be studied in this section. They accommodate and are responsive to the Afghan guidelines for earthquake-resistant constructions since Kabul is geographically located in Zone C, with moderate earthquakes (Guideline, 2003). Earth buildings are often not sufficiently strong to withstand natural disasters and seismic shocks. Hence, simple rectangular forms with a symmetric plan and cross-walls are considered for the design of the models. In line with the guidelines (Guideline, 2003) and Blondet et al.'s (2011) propositions for seismically stable buildings, the design suggests firm stone foundations, wall thicknesses proportional to the wall length and height, and that the length of the openings are minimised according to the seismic guidelines, and with a relatively lightweight roof. Moreover, for the wooden structure, on top of the walls, under the poplar wood, two wooden rings (50 x 50) mm are to be laid on the entire walls, and they are to be connected to the foundations by vertical wood columns (50 x 50) mm on the corners of the walls. This would help the equal distribution of the roof weight, resistance against seismic shocks, and improve the stability of the wall against humidity and water penetration. Two models (A and B) are one story, accounting for the above precautions, and they have considerable stability against moderate seismic shocks; however, the third (Model C) has two stories, for which the horizontal (lintel and ceiling bands) and vertical reinforcements must be tied up with the lintels and the foundation. The ground floor should be solid, and the second floor needs to be light with a soft structure (Minke,

2012). This will improve the model's resistance to the walls and roofs collapsing during an earthquake.

Some general information about the three models' materials, thicknesses, and key elements are given in the following:

Foundations: these measure down to 400 mm below ground level, and they constitute a 600 mm wide rigid foundation made of stone and concrete mortar, also used for the walls. The stone foundation reaches 600 mm high above ground level, which can protect the walls from snow, water, and humidity.

Wall: a sequence of wall thicknesses (100 to 1000 mm) was analysed in Chapter 5 to find the optimum wall thickness. The results of this showed that the responsive thickness to the cold climate of Kabul is around 500 mm. This includes the thickness of the CEB wall and the protective plaster. Based on these analyses, 505 mm of wall thickness for the prototype models was selected. The true thickness of the partition walls for the kitchen and toilets are 145 mm.

Plaster: for the exterior wall plaster, 30 mm of thatch (soil-straw) with a mixture property of 127 kg of straw per cubic metre of soil (8 % straw) was considered (Baseri et al., 2016). However, for the interior plaster, there are two solutions: 1) the same plaster used for the exterior walls should be applied; or 2) the approved mix design A for the mortar in Chapter 4 (with a mix of 1 kg of soil, 2 kg of river sand, and 0.75 kg of water) could be applied. This mix design has an appropriate resistance to cracks and a good cohesion. The toilet interior walls has sand and cement plaster and tile, which would enable the walls to tolerate the humidity.

Floor: for the floor, 550 mm of soil compacted and then 50 mm of thatch is to be applied in two layers. It is to be a traditional flooring, found in early earth buildings. However, the hall floor has 50 mm of concrete, and the kitchen and toilet floors are to be decorated with tiles.

Note: the deck in front of the building has 50 mm of concrete finishing and gravel base to better tolerate humidity and water.

Roof: a combination of traditional roofing with modern roof construction methods is to be designed. From the bottom up, the following layers are considered: 150 mm of poplar wood, 10 mm of plywood, a mix of soil, straw, or Ghuragel (275 mm), dry soil

(50 mm), solid concrete (50 mm), and the isogam waterproof layer (4.8 mm). The concrete layer functions as a hard base for joining the roof with the isogam layer.

Openings: the standard insulated double glazing (air), wood frame windows with 1,600 W/(m².K) U-value has been selected for the exterior windows. For the interior windows and all doors, the locally available windows and doors that are produced in Kabul are to be used.

Wiring: the building will be equipped with wiring for electricity and phone lines, ready to connect to the central electrical systems. However, since there is no central gas system in Kabul, this has not been considered in this study.

Painting: water-based paint (75 %) is to be applied only inside the rooms, kitchen, and hall. The outside surfaces will use soil and straw plaster, without any paint.

Note. If Russian structured timber is used instead of poplar wood for the roofing, then it makes it possible to locate the 275 mm soil and straw layer between the two timbers, and the plywood could be nailed to the bottom of the timber. This can reduce the total height of the roof and provide a nice flat timber-plywood roof inside the house.

Sewage system: the pit-latrines will be connected to the central sewage system where possible; otherwise, it will be joined up with the septic tank that covers the entire residential area.

Description of the prototype models:

Model A is a one-story courtyard house (see Figs: 127, 128, and 129), consisting of thirty grids of 6.25 m², covering a plot of 187.5 m², with approximately ten grids for the buildings and twenty for the courtyard. In each unit of eight homes, there is a right and left plot (houses). Each plot has one bedroom, living room, kitchen, bathroom, and a pit-latrines in the corner of the courtyard. 38.64 % of the south-facing wall is covered by openings. Based on the analyses of the sunshine angles in Kabul, 600 mm of overhang has been designed on the south wall of Models A and B to protect the rooms from the summer sunlight. Depending on the location of the courtyard (corner or centre), there are to be one or two shared walls in each building. The pit-latrines must be connected to the central canalisation systems, rather than using manual traditional evacuation methods, which exist in the city.

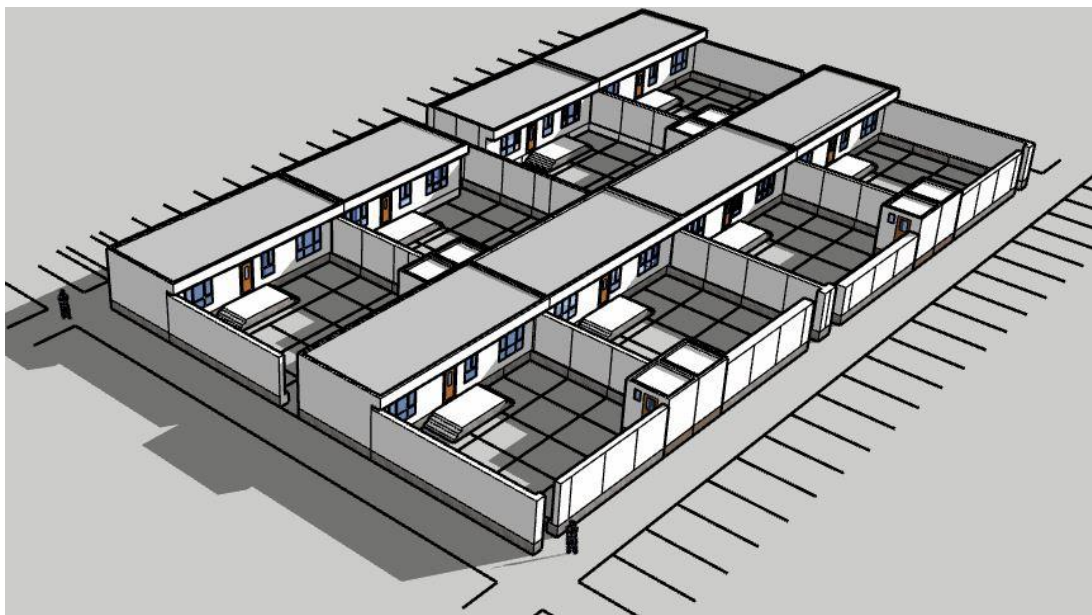
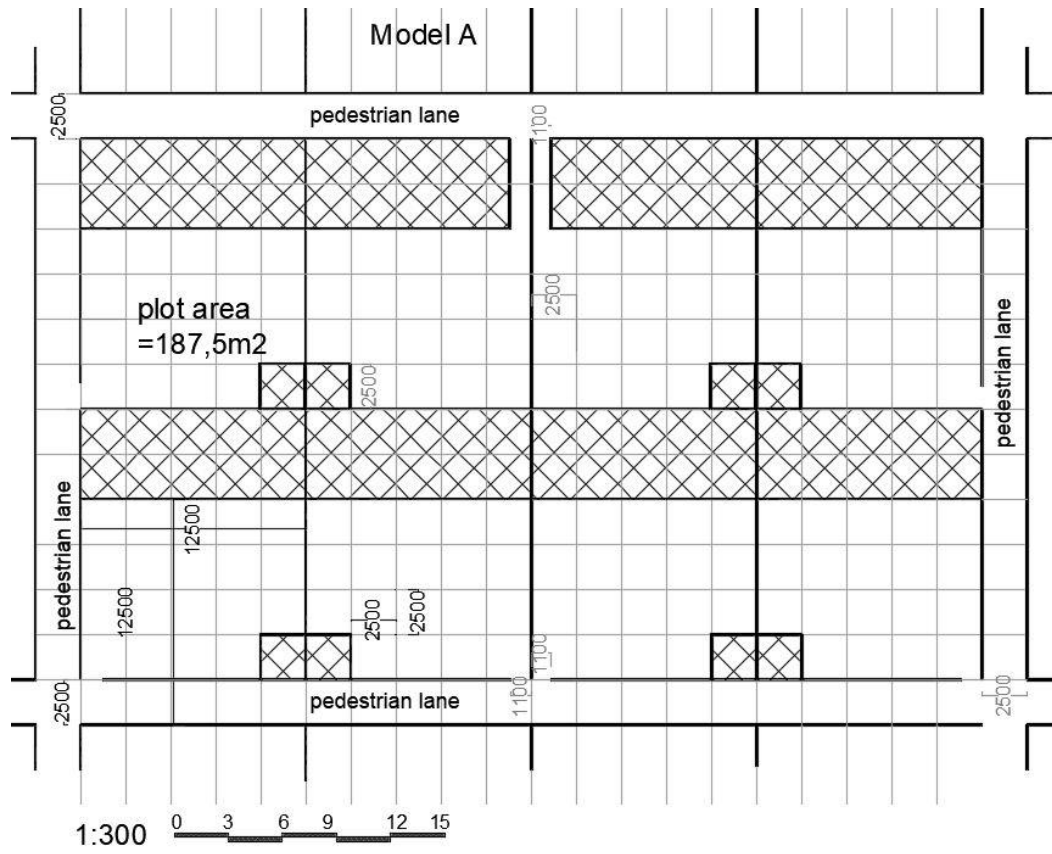
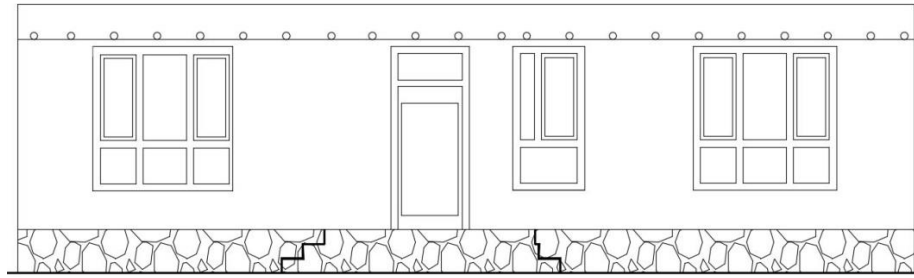


Figure 127: Model A: units of the eight-plot layout with a 3D view



South elevation

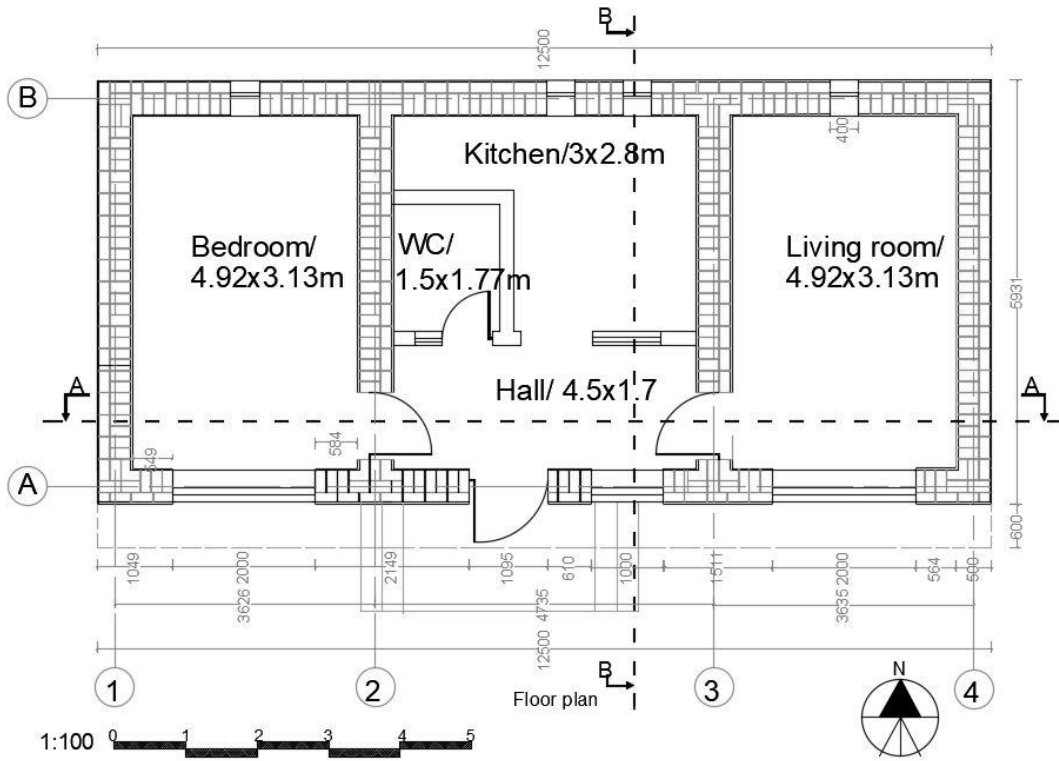


Figure 128: Model A: plan and south elevation

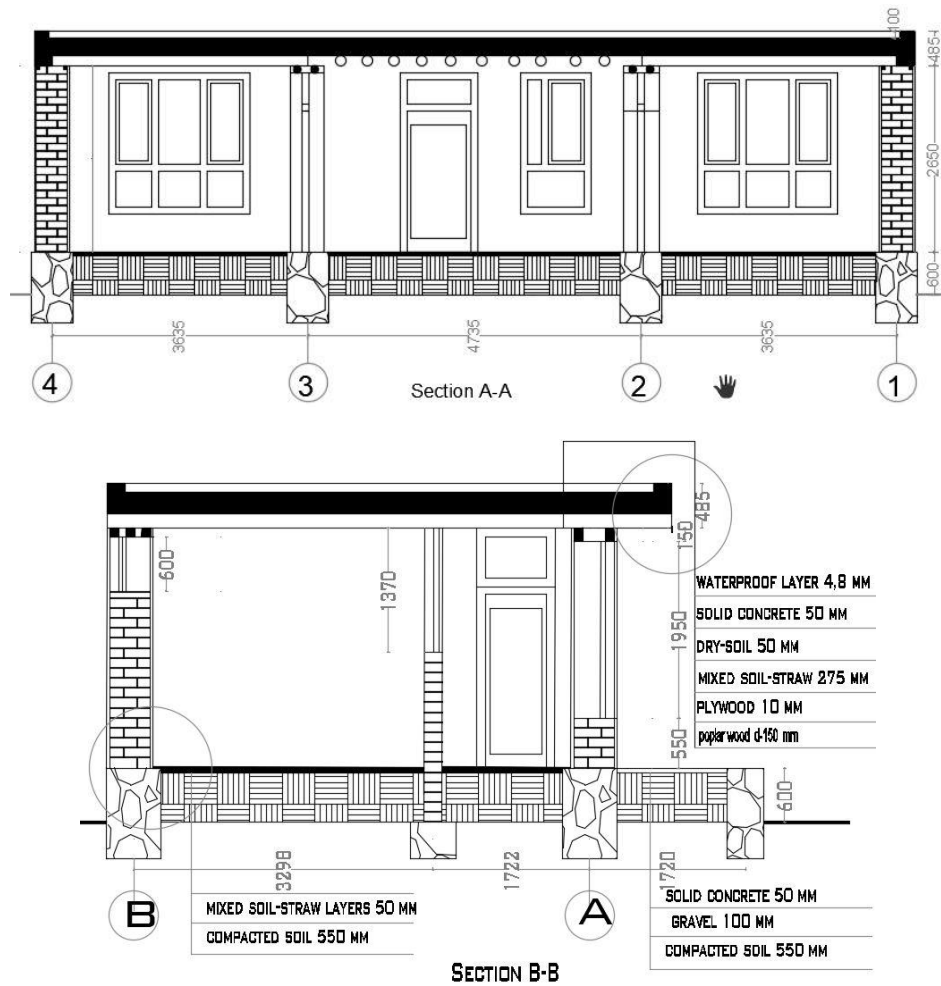


Figure 129: Model A: cross-section

Model B is a one-story courtyard house (see Figs: 130, 131, and 132), consisting of thirty-five grids of 6.25m², covering a plot 218.75m², the buildings within fourteen grids, and twenty-one grids are allocated for the courtyards. The number of shared walls is the same as Model A. In each plot (right or left), there are two bedrooms, a living room, a kitchen, a bathroom, and a traditional pit-latrine (see also Fig. 130). The openings in the south-facing walls count for 38.64 % of the area.

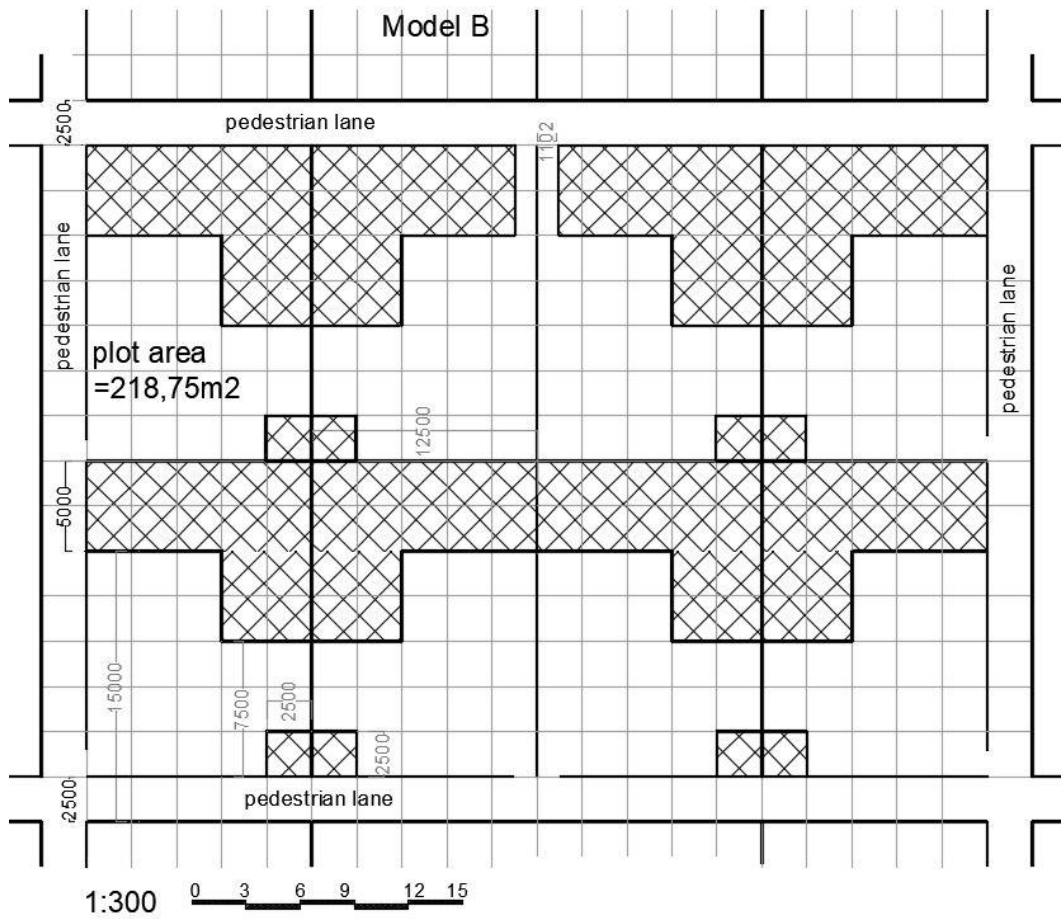
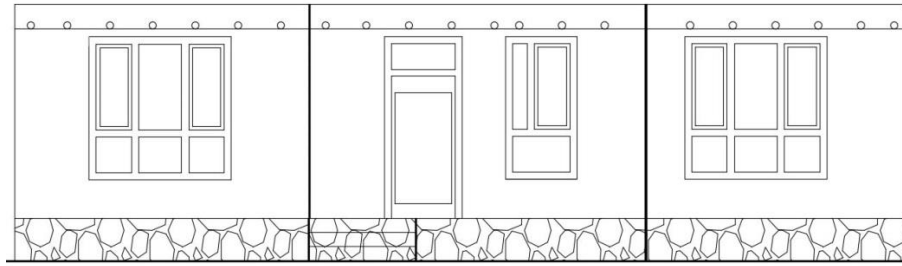


Figure 130: Model B: units of the eight-plot layout with a 3D view



South elevation

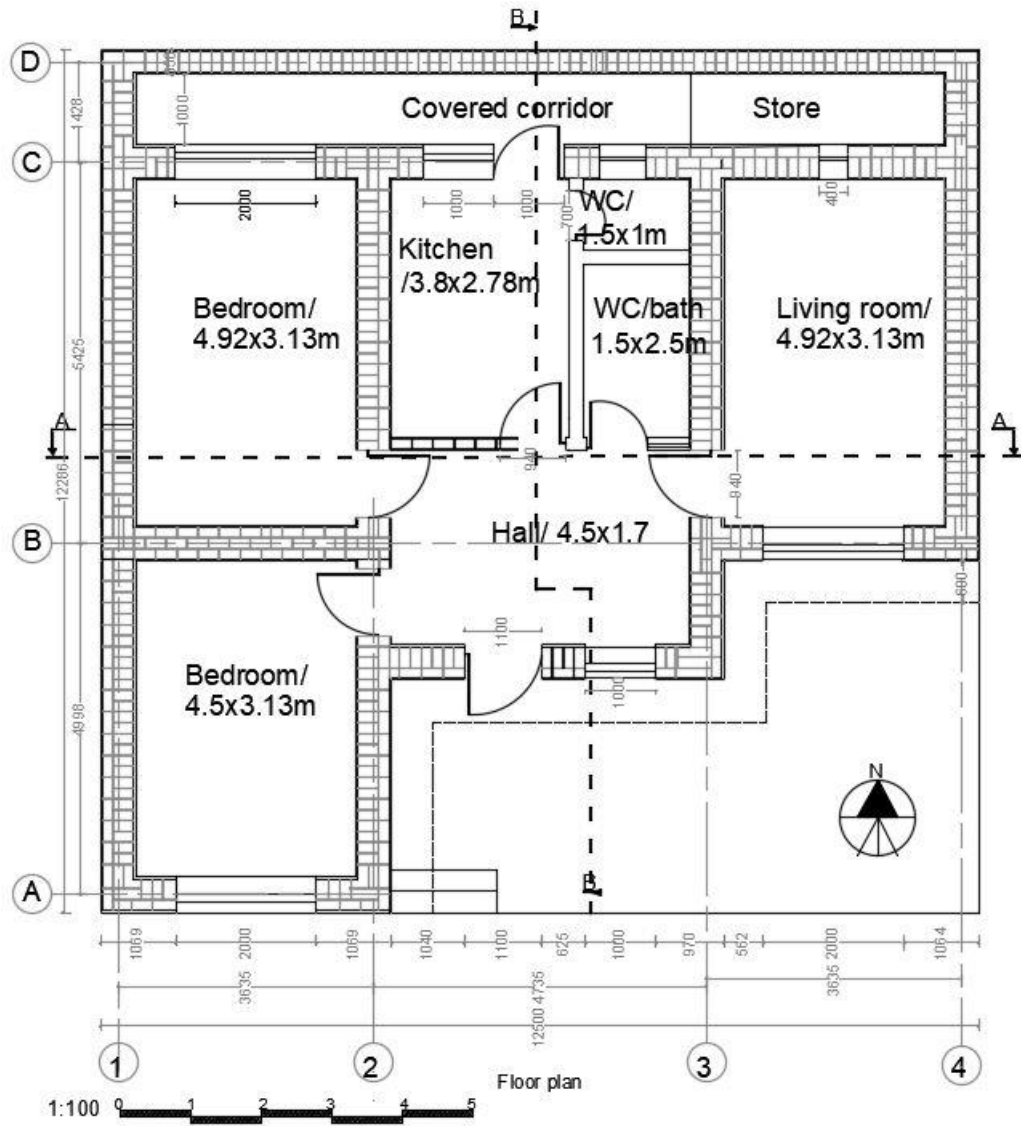


Figure 131: Model B: plan and elevation

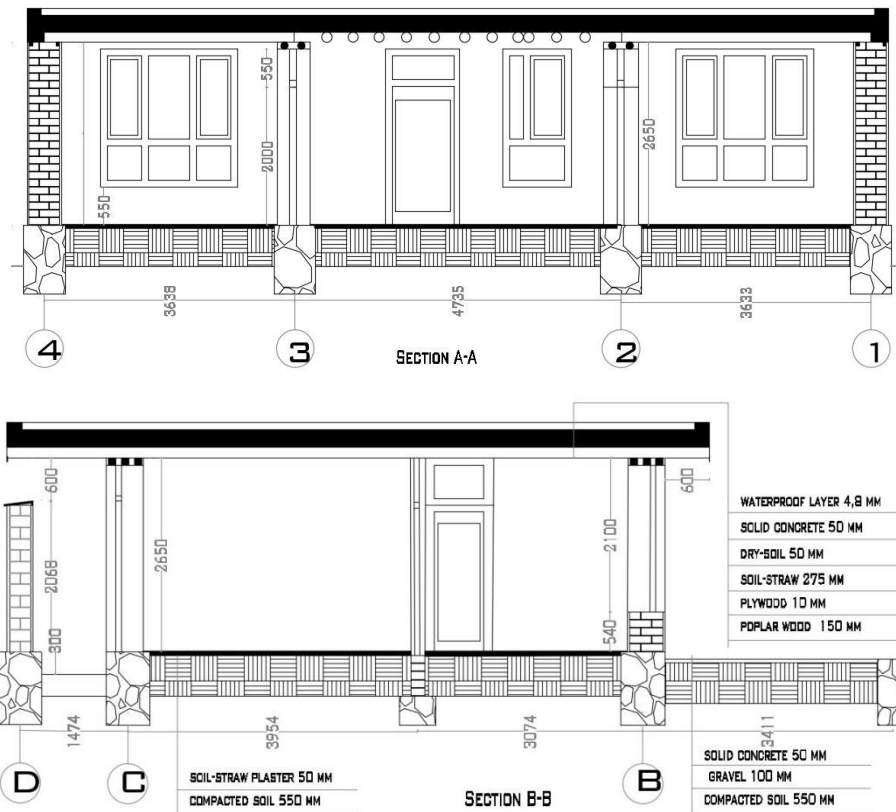


Figure 132: Model B: long and wide cross-sections

Model C is a two-story courtyard house (see Figs: 133, 134, and 135), consisting of thirty-five grids of 6.25 m², covering a plot of 218.75 m², and approximately ten grids cover the building area, while twenty-five grids have been allocated for the courtyards. On the first floor, there is one living room, a kitchen, and a bathroom. On the second floor, there are three bedrooms, two above the living room and kitchen and one over the pedestrian walkway (see Fig. 134). The analyses showed that 800 mm of overhang was to be designed on the south wall to protect the rooms from the summer sunshine. This type of residential housing exists in traditional neighbourhoods in Kabul (Hakim-Ebrahim and Devillers 2022). The room covering the pedestrian lane adds extra usable space to the building and provides shade to the lane. 25 % of the south-facing wall is dedicated for openings.

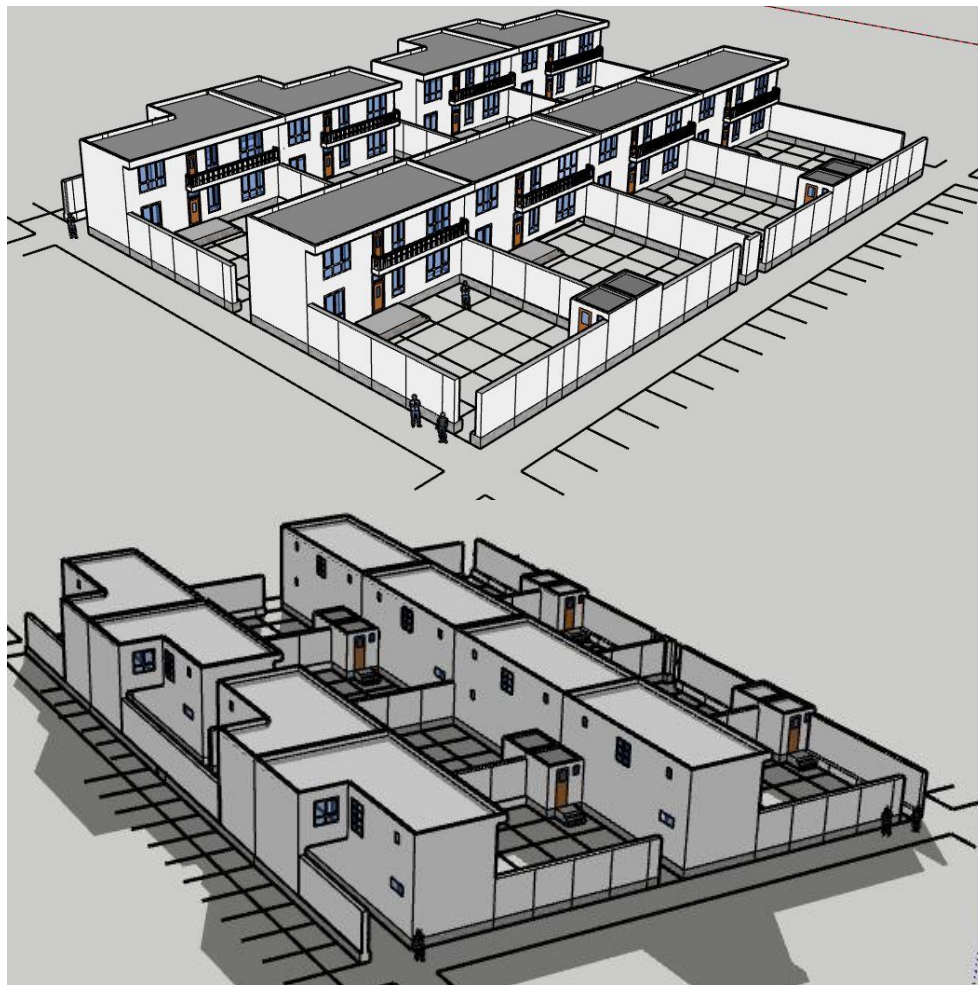
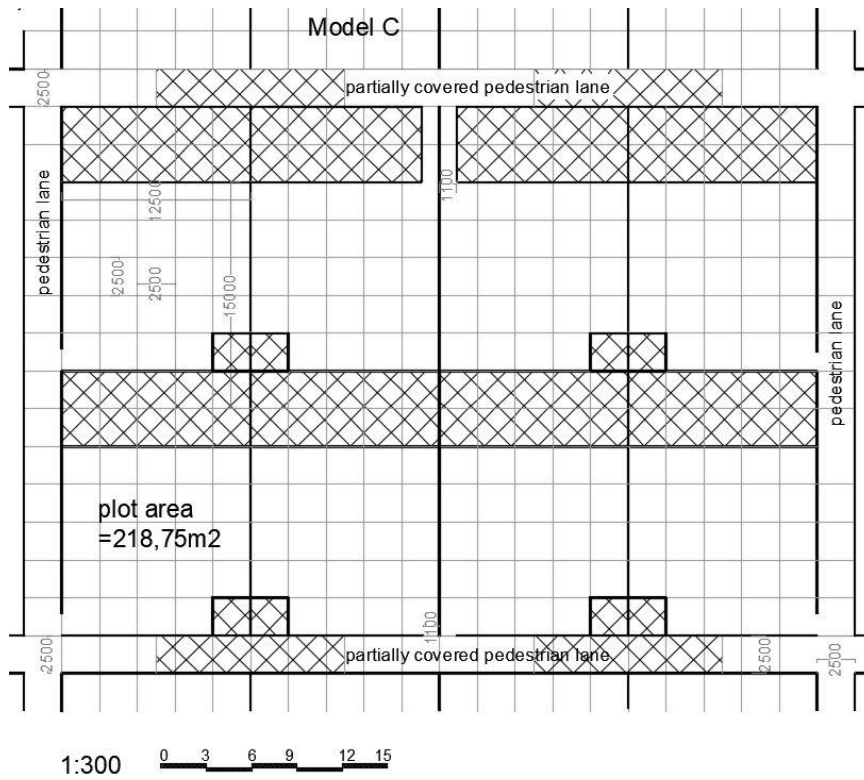


Figure 133: Model C: units of the eight-plot layout with a 3D view and extra room over the walkway

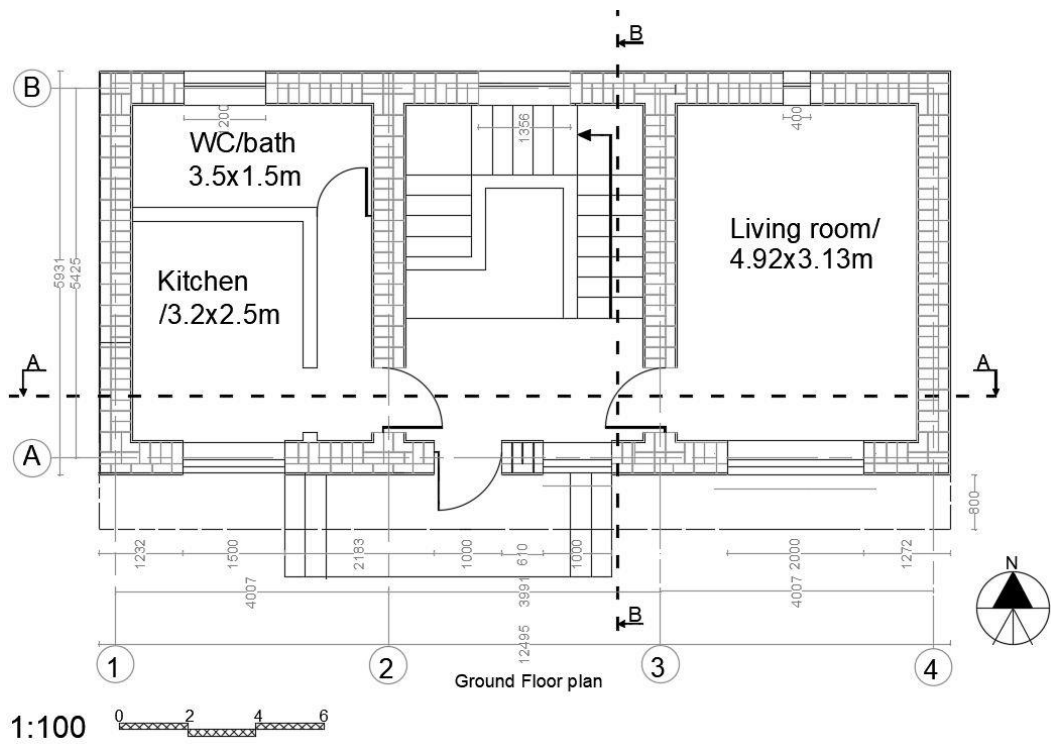
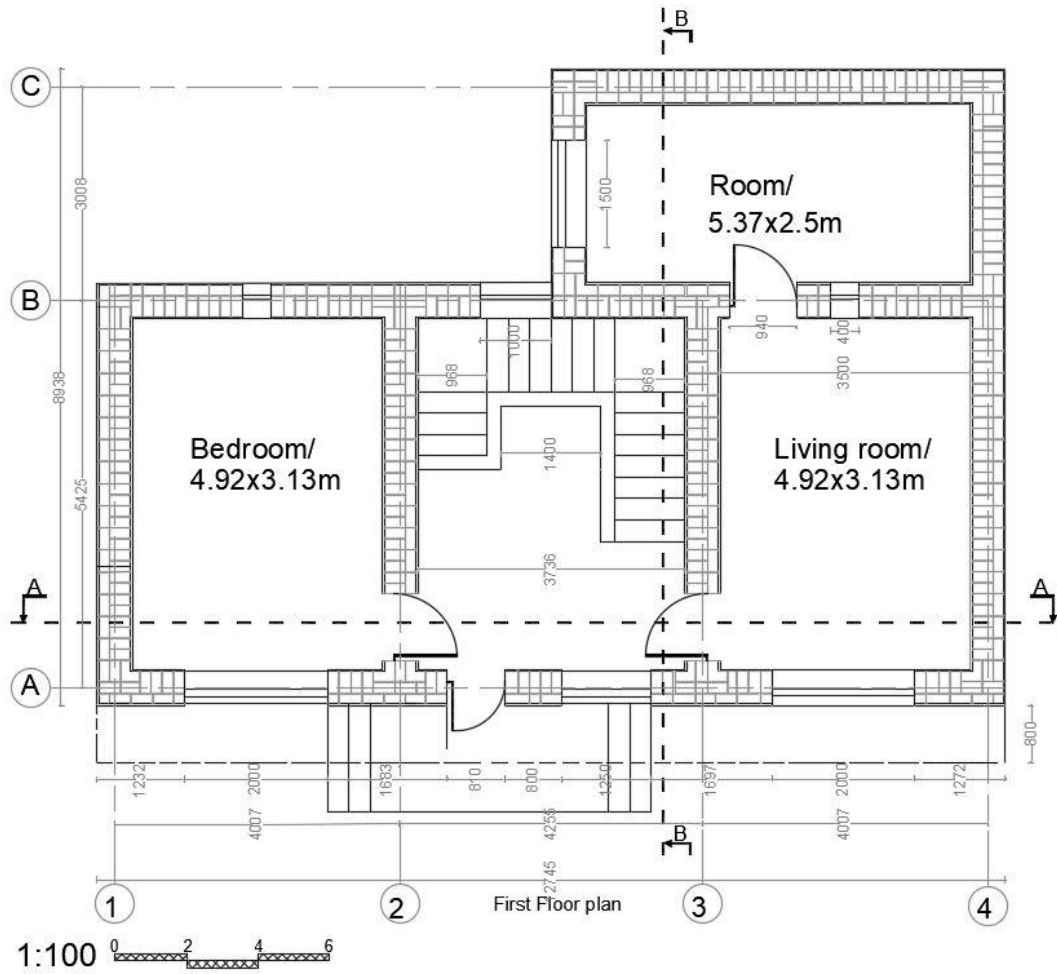
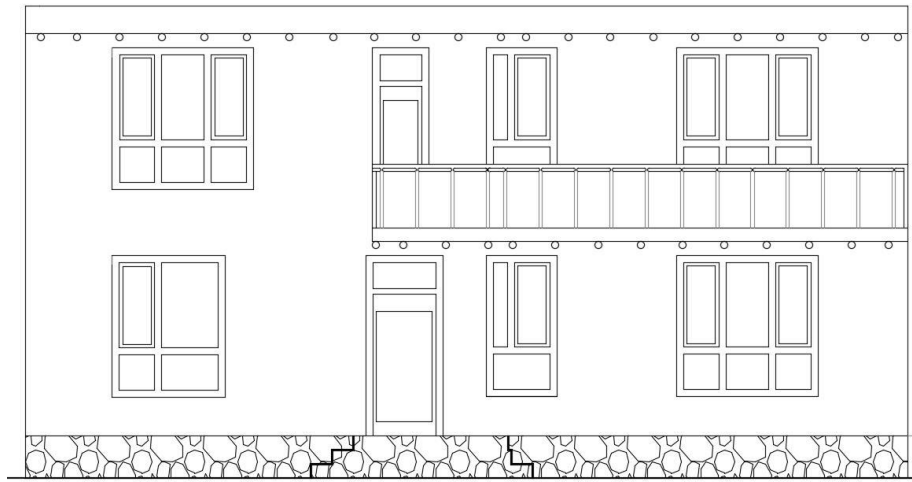
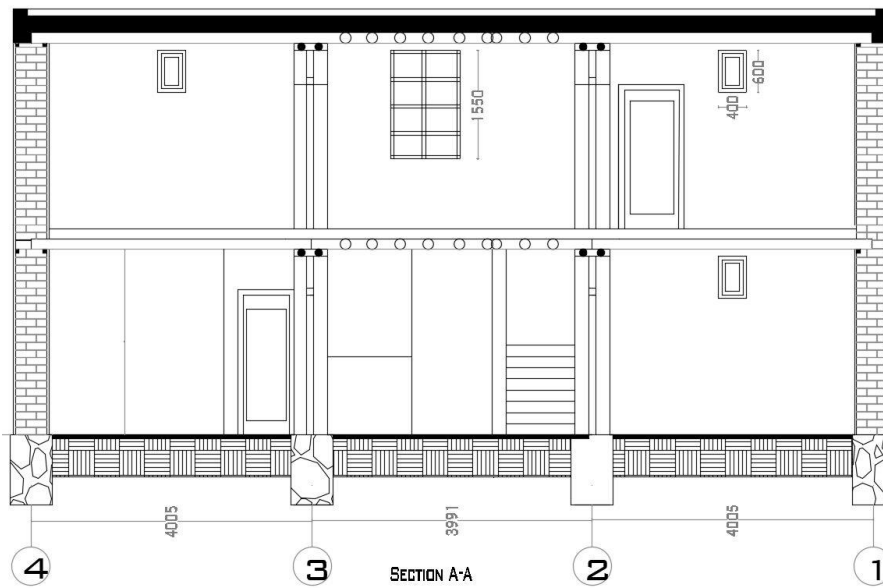


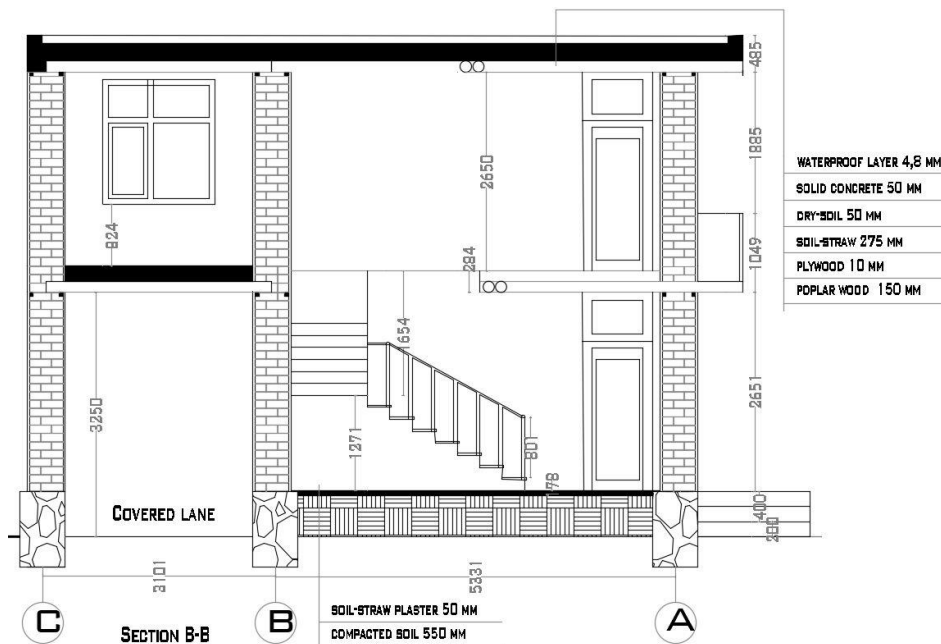
Figure 134: Model C: ground-floor and first-floor plans



SOUTH ELEVATION



SECTION A-A



SECTION B-B

Figure 135: Model C: elevation and cross-sections (A & B)

For the construction of the affordable housing in Kabul, it is possible to build a residential area with one model or combine two or three models (see Fig. 136). This will provide a better layout and secure a safe passage by cutting long east-western lanes into zigzagging ones. Moreover, it can accommodate various sizes of families within the neighbourhood.

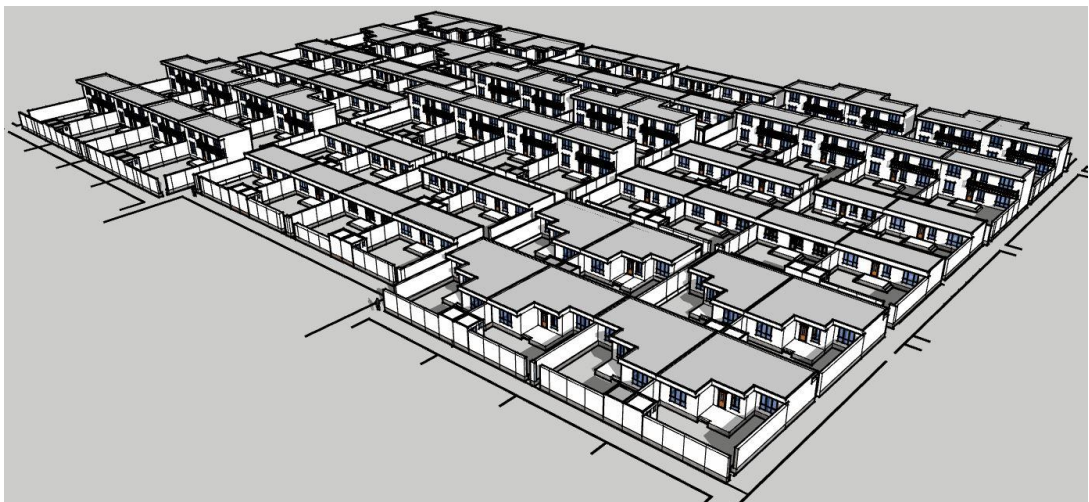
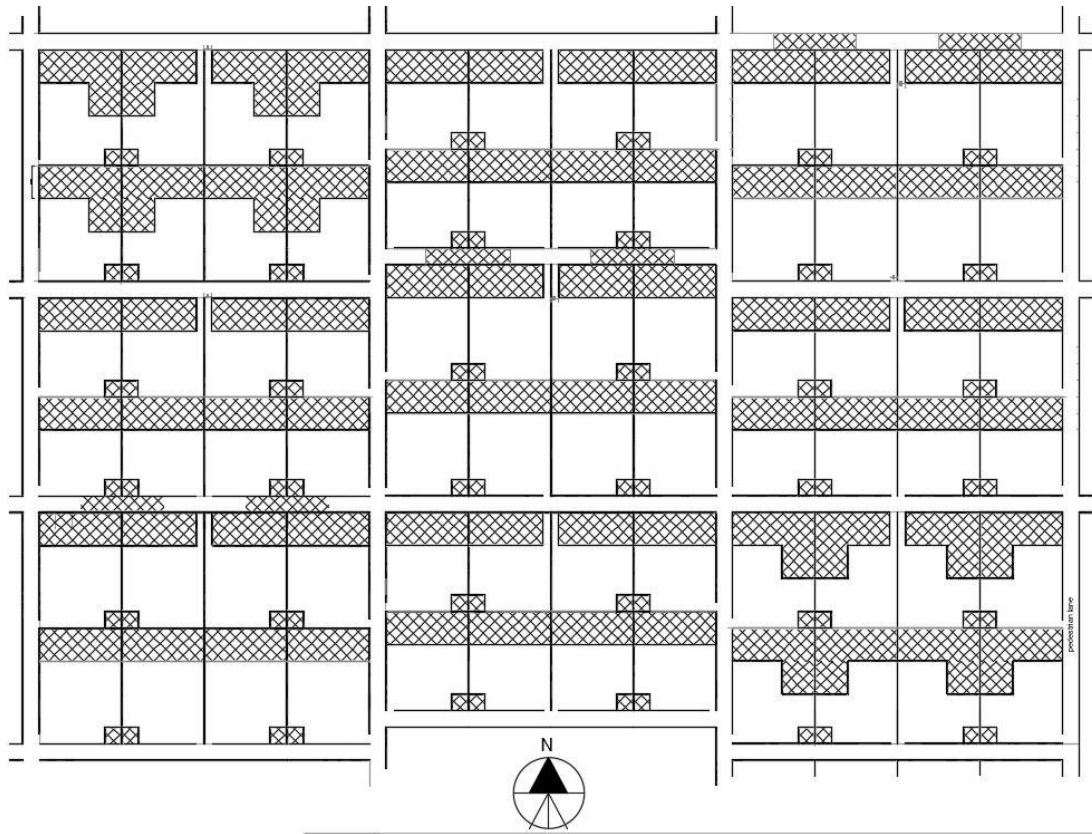


Figure 136: Sample area combining the three prototype models (A, B, and C)

6.5 Design concept

The concept of the design for this research starts with the following factors: affordability, availability, passive design strategy, and environmentally friendly houses. Affordability is important for low-income people in urgent need for shelter. The recent four decades of war have affected all Afghans, especially the recent political change, which resulted in the fall of the country to the Taliban. The majority of low-income citizens such as government employees, schoolteachers, foreign organisation employees, and small traders lost their income after the governmental change.

In addition, the years of war destroyed the economy in the country, and it is not feasible to import expensive and modern construction materials for low-rise residential houses. Local material can play a role, since they have been used for years, and Kabul is rich in such substances, including soil and stone. The use of local materials will significantly reduce manufacturing and transportation costs, which account for 35 % of a material's embodied energy (Yu et al., 2022). By building with earth, traditionally used for centuries in Kabul, people already have a certain amount of knowledge, especially in constructions using CEB since it is a familiar material. More importantly, it is possible to industrialise CEB production for mass-construction so that is made quicker and with a better quality. However, onsite manual production could be a priority for this project, which could provide jobs and preserve knowledge of traditional earth constructions. The manual pressed block machine is available in the Kabul market and has the ability of manually producing CEB on construction sites.

The passive design strategy is achieved by well-orientated, cross-ventilated, and well-designed envelopes or surrounds of the building. The long access of the proposed buildings is located along the east-west axis, with large openings to the south to gain maximum solar heat during winter and to minimise summer sun, with the 600 mm of overhang on the south elevation (see Fig. 137). The simulation in the ArchiWIZARD software shows that slightly changing the orientation of the building towards the east or west axis ($\pm 15^\circ$ degree) does not affect the solar gains and energy demands of the building. This means that if the building orientation changes between -15° and $+15^\circ$ (see Fig. 138), it does not affect energy demands of the building. The proposed models, rooms, and buildings have shared walls to reduce such energy demand. Cross-natural ventilation is supported by designing the windows in the north and south walls (see Fig.

138), and which can also be applied to the rooms and kitchen. The green courtyard, in front of the building, provides fresh air to the rooms during the day and at night.

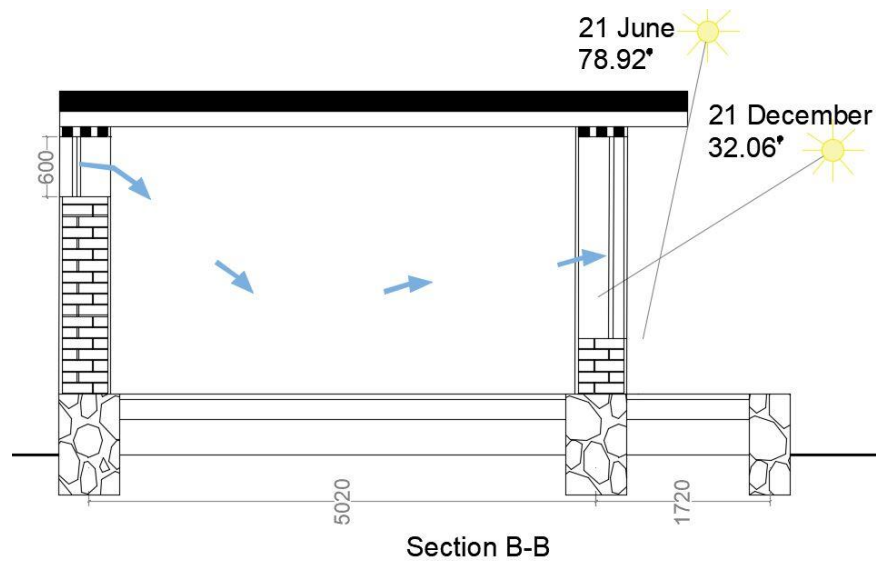


Figure 137: Natural ventilation and sun angles during the winter and summer periods

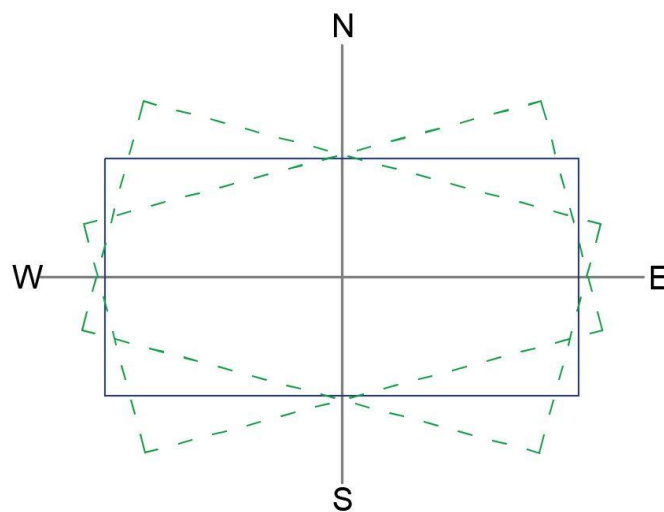


Figure 138: Changing orientation of the building's long access ($\pm 15^\circ$)

The CEB made with raw soil is environmentally friendly, and local materials without cement and chemical additives using manual machines have been considered to produce these earth constructions. It is recyclable, reusable, and at the end of life is returnable to the land. Soil has a good thermal insulation performance, and this can help to reduce the energy demands of the building. Traditional heating systems proposed to heat the building, such as oak wood and coal are locally available materials, constituting also the main source of heating for these affordable housing models.

6.6 Heating and cooling systems

The analysis on the energy demand of the houses in Kabul shows that there is more energy demand for heating the house compared to cooling it. The findings of the climate analyses in Chapter 1 (see Fig. 12) showed that Kabul has six months of cold days and cold nights in which the houses need heating, and the thermal stress is around 2,840 °C degree-days per year. In Kabul heating accounts for 91.1 % of the energy demand in contrast to 8.9 % for the cooling. This was confirmed by analysing the heating energy demand of the model house in ArchiWIZARD, where the annual heating energy demand was 6,377 kWh. The comparison of the two data (see Fig. 139) shows a good correlation. Both analyses confirm that the housing energy demand is high during January, February, December, November, March, and October . Therefore, only the heating energy will be analysed for the proposed model, and the cooling energy demand is not considered.

Various methods of heating houses in Kabul exist:

1. A limited number of people have access to central heating systems, including those who live in apartments built during the 1960s (also known as microrayons). Moreover, some modern townships and private apartments have private heating systems in their buildings. This, however, counts for less than 1 % of the Kabul population.
2. Traditional underfloor heating systems were used mainly in the suburban areas of Kabul, but the cattle keepers and those who have animals use animal dung and waste from their lands for heating and cooking their daily food. This system needs more energy, and the heating material must last a long time to keep the floor warm.
3. Wood and coal have been traditionally used, and they are considered as the main source of heating in a building. Traditional iron sheet stoves (see Fig. 140) have been applied to heat the rooms during winter. The stove is available locally in various shapes and sizes, and it currently is the main method of heating houses in Kabul. This method will be considered for the proposed model of low-cost housing in Kabul. This cost is less than the two aforementioned methods and is readily available in the city.

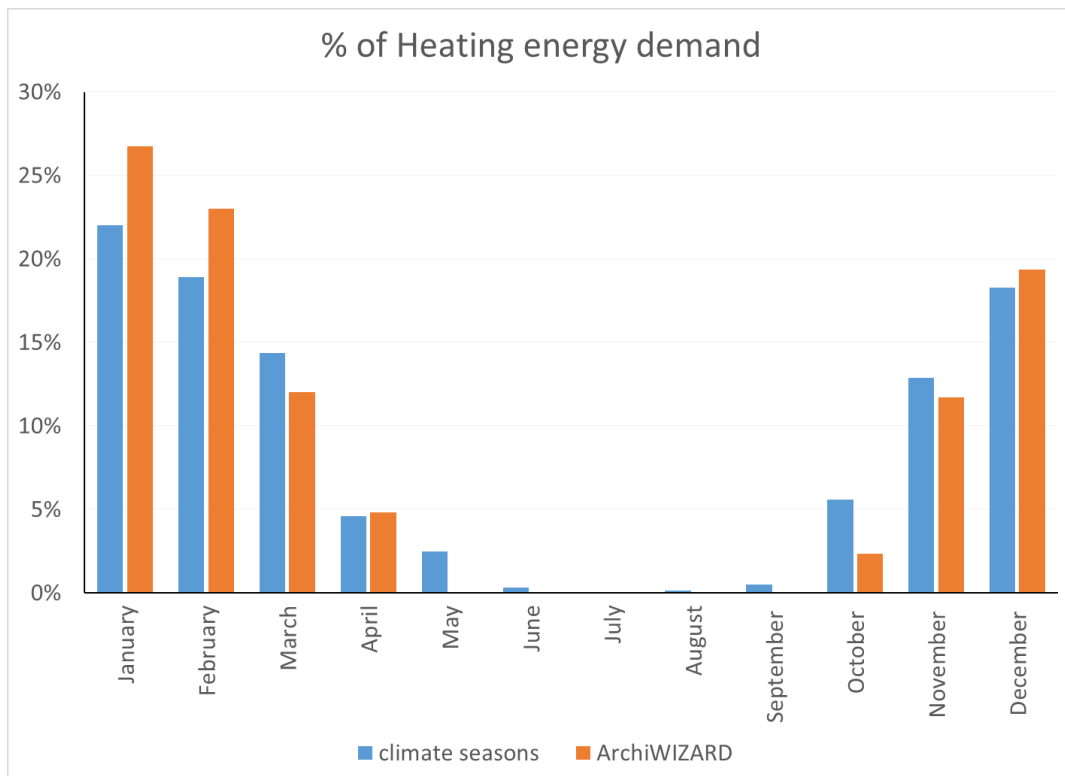


Figure 139: Comparison of the monthly heating energy demand for Kabul



Figure 140: From left to right: traditional wooden and coal stoves

6.7. Cost analyses

Detailed cost analyses have been carried out on model A, considering the optimised composite wall thickness (505 mm). This includes the cost of the building, traditional pit-latrines, and courtyard walls and door. Detailed information about the construction materials are indicated in Chapter 5 (the prototype model design section). One wall of

the building and two walls of the courtyard are shared with the neighbouring houses, and thus half the cost of those walls is considered in this analysis. Since the affordable housing for Kabul is designed to be constructed as formal residential areas, not as individual houses, it is assumed that the central electricity, water, and sewage systems should be installed by the authority. Therefore, they are not calculated in the cost analyses. Since in Kabul, wood is used as the main source of heating homes during winter, so oak wood is considered as a viable source of heating, where 538 kg of oak produces 2,000 kWh of energy. The cost breakdown is summarised in Table 17. However, a detailed cost analyses for each item is shown in Table 18.

No	Item	Unit	Amount	Unit cost \$	Total cost \$	Cost \$/m ²
1	Building with overhang	m ²	82.5	-	4,617.6	55.97
2	Pit-latrine	//	4.5	-	312	69.3
3	Building with pit-latrine	//	87	-	4,929.6	56.6
4	Courtyard	m ²	30.4	19.5	592.8	-
5	Total construction cost for the complete model				5,522.5 \$	
	Heating energy cost	kWh	6,377/year	0.03725	237.5 \$	-

Table 17: Cost breakdown of the model house

The UN-Habitat (2017) models built with RE, interlocking mud block, and concrete block cost 109.12, 77.66, and 94.23 US dollars per square metre, respectively. The cost/m² of the model house proposed during this study (56.6 \$) is very cheap. Similarly, comparing this cost with the MUDL (2018) models proposed with pakhsa, stone, and fired brick, they cost 54.9, 64.8, and 70 US dollars per square metre, respectively. The cost/m² of the proposed model is similar to the pakhsa-made house, but relatively cheaper than the stone and fired-brick one.

With this construction cost, if the government provided the land and basic infrastructure for the affordable housing programme in Kabul, the homeowners could pay back the money (they will spend on the construction of the courtyard house) over 15 years, by paying 1 \$ per day. Considering the life of the CEB house of 50 years, the total heating energy during this period would be equal to 31,885 kWh, which will cost 11,877 \$, together with the construction costs (11,877 + 5,522.5 = 17,399.6 \$). During these 50 years, the average annual cost of construction and energy would be equal to 347.9 \$ per year (see Tab. 18).

No	Item	Unit	Quantity	Unit cost	Total cost
A	FOUNDATION				
1	Excavation	m ³	14.28	3.57	50.9796
2	Stone masonry (M200),1:5	//	30.6	15.7	480.42
3	Floor filled with soil and compacted	//	30	2	60
	Labour: skilled/unskilled	man	ls	198	198
B	WALL CONSTRUCTION				0
	CEB	no	9,570	0.04	382.8
	Int mud-straw plaster	m ²	143	0.288	41.184
	Ext mud-straw plaster	//	108	0.288	31.104
	Int painting	//	143	1.5	214.5
	Labour: skilled/unskilled	man	ls	656	656
C	ROOF				0
	Poplar wood (Φ 15 cm)	m	96	1.87	179.52
	Poplar wood (Φ 10 cm)	//	78	1.25	97.5
	Lintel (Φ 15 cm)	//	40	1.87	74.8
	Wood ring (Φ 5 cm)	//	80	0.625	50
	Wood columns (Φ 10 cm)	//	41.6	1.25	52
	Plywood	m ²	50	2.16	108
	Mud-straw (Ghuragel)	m ³	20	9.5	190
	Dry soil	//	3.69	5	18.45
	Concrete	//	3.69	40	147.6
	Gutter from GI sheet	m	5.3	3	15.9
	Insulation (isogam 4.8 mm)	m ²	80	2.3	184
	Labour: skilled/unskilled	man	ls	110	110
D	DOORS & WINDOWS				0
	Int doors	m ²	10.6	20	212
	Ext doors	//	2.5	20	50
	Int windows	//	2	11	22
	Ext windows	//	11.7	27	315.9
E	LUMP SUM ITEMS				0
	Electricity	ls	1	150	150
	Water tank	//	1	75	75
	Kitchen	//	1	300	300
	Toilet	//	1	150	150
	Pit-latrine	//	1	312	312
	Total cost of building and pit-latrine				4,929,657.6
	m² cost of building plus pit-latrine	m ²	4,929,657.6	87	56,662,731.03
F	Courtyard	m	30.4	19.5	592.8
	Total cost of building, pit-latrine, and courtyard				5,522,457.6
G	Heating energy cost/year	kWh	6,377	0.03725	237.5

Table 18: Proposed model and detailed cost analysis

6.8 Conclusion

This chapter described the existing modes for low-cost housing, and it proposed three building models for the affordable housing programme in Kabul. Model A and B are one story with two south-facing rooms, while model C had two stories with three south-facing rooms and one room over the pedestrian lane. The design concept expressed that the models have to provide an optimum solution for low-cost housing and be environmentally friendly and in-line with a passive design strategy. The locally available heating (of wood and coal stoves) and cross-natural ventilation systems have also been proposed, and detailed recommendations have been made. A complete cost analysis: cost of materials, labour, and heating energy of the proposed building in Chapter 5 was calculated and presented.

GENERAL CONCLUSIONS

In Afghanistan, as with many other developing countries, a lack of appropriate shelter is common, and it is a challenge to address this shortage adequately. This is more visible in the larger cities where the majority of Afghans are living. A great majority of the people live in informal settlements, with a low quality of life. In Kabul city, it counts for 80 % of the population (World Bank, 2006).

During this doctoral research, Kabul was studied, alongside its domestic architecture, mainly consisting of buildings constructed from earth. Sun-dried brick, pakhsa, and stone are the main building elements under study, and they are found in abundance in the country. However, building with earth suffers from the pitfalls of traditional construction techniques. These methods have been used for centuries, and people know how to implement them.

Moreover, to overcome the shortage of housing in Kabul, cheap local (environmentally friendly) materials should play a role. However, for this huge shortage, traditional methods are not responsive to current citizen nor building needs. It takes a long time to build a construction of earth and especially since it can have a weak mechanical strength and poor durability. This is because it is built using these traditional methods. Hence, the use of traditional earth construction is not a good solution for the mass construction of low-cost housing in Kabul. There is a paucity of research about modern earth construction methods in the country that can be applied to earth housing. Therefore, this research provides the basis for knowing how to build affordable houses with soil using local materials but with modern earth construction techniques that demonstrates improved strength and durability.

For this, the soil from three regions in Kabul, Arghandi, Band-e-Ghazi and Deh-Sabz, were studied to find out if they were suitable for modern earth construction techniques. After a series of experiments and analyses, the results showed that they are all suitable. Three different earth elements: sun-dried brick, compressed earth block (CEB), and compressed stabilised earth block (CSEB) were also produced. The compressive strength of these elements was compared. Considering the environmental issues, the stabilisation of earth with Portland cement was not efficient, with its consumption of a large amount of cement, and it provided a weak compressive strength. Therefore, CSEB was not considered for further analyses. The dry compressive strength of CEB was

higher than sun-dried brick, while the thermal conductivity of both elements was similar. This confirmed that the most suitable technique for the production of mud brick in Kabul is CEB. Considering that compressive strength is a major factor, CEB made with Deh-Sabz soil was selected for Kabul's affordable housing programme. Deh-Sabz clayed soil contains 98 % clay and silt and 2 % sand. The results of the water absorption test on the CEB confirmed little resistance against erosion, and that CEB was weak against direct contact with water. Therefore, low-cost housing for Kabul must have rigid stone foundations, and the enveloping walls must be kept away from water and humidity with the use of earth-straw plaster. Similar precautions need to be taken for the roofs of the houses.

Then a soil- and sand -based mortar to enable building the CEB dwelling was selected based on the guide to good practice on earth construction and earth coating (Savira and Suharsono, 2020). The selected mortar had a ratio of 1 kg of Deh-Sabz soil, 2 kg of river sand, and 0.5 kg of water.

Then, considering the Kabul climate, the optimum wall thickness (505 mm) based on the thermal performance of the wall and energy demands of the model house was selected. Based on the design concept, the traditional architecture of Kabul, the local culture, and the selected CEB and mortar, three prototype models were designed: with one, two, and three bedrooms. Out of these, the one-bedroom house was further analysed. It is a courtyard house that can accommodate an average Afghan family of 6-to-7 persons (UN-Habitat, 2017). Kabul is geographically located in Zone C with moderate earthquakes (Guidelines, 2003). Therefore, the proposed models are responsive to moderate earthquakes. Hence, simple rectangular forms with symmetric plans and cross-walls have been considered during the design. In line with the guidelines (2003) and Blondet (2011) the design has a firm stone foundation, with wall thicknesses proportional to the wall length and height, the length of the openings minimised according to the seismic guidelines, and a relatively lightweight roof. A wooden structure connects the foundation with the walls and the roof.

Cross ventilation with small inlets and big outlets, (Hassan, 1978) according to the wind direction, have also been designed. Part of the south-facing wall (38.64 %) is covered with openings, and 600 mm of roof overhangs to protect the southern rooms from the summer sun. The heating energy demand in Kabul city was further analysed. Wood and

coal are traditionally used, and they have considered as the main source of heating in the building. The cost per square meter of the building and pit-latrines equal to 56.6 \$.

This thesis provides an in-depth study (analytical and experimental) and proposes practical solutions to the problem of affordable housing construction in Afghanistan in general and for Kabul in particular. Experiments on Kabul soil and earthen elements were conducted, which have not been previously implemented. There is an absence of research on this subject, hence this study providing ground-breaking evidence to address a critical and current problem in housing. In view of the limitations to executing this thesis, the COVID-19 pandemic presented certain difficulties to implementing the experiments, but which were overcome. Moreover, recent political changes in the Afghanistan made it difficult for the author to carry out the research due to the ongoing stress experienced during this time.

Fortunately, despite these barriers, the soil and earthen elements were able to be studied during this doctoral research. However, another limitation is that it was not possible to develop soil-straw panels with less thermal conductivity to improve the thermal performance of the enveloping walls for the proposed model. This could be a good topic for professionals and researchers. Moreover, there are modern earth construction techniques that are well-suited to the Afghan climate, and they are environmentally friendly. I would recommend future experimental research on the prefabricated rammed earth (RE) and poured earth construction techniques and their application in Afghanistan. These techniques could help the construction of public buildings, especially in the health and agricultural sectors.

To conclude the thesis, all the results achieved during this study are based on laboratory experiments; it would be helpful to develop a life-sized scale of the project on the same soil and earth elements to compare the results. I would suggest construction of at least three sample houses from each of the three aforementioned models. This could help to further determine the practicality of the proposed building models for Kabul. A further area of recommended future study is the industrialisation of the proposed CEB to facilitate the mass production of affordable housing construction.

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