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EDITORIAL

Integrated Water Resource Management and Climate Change

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The documentation of local progress assistance from climate change qualification is a likely inspiring feature to attain this. But, there is a deficiency of applied instances of how climate change qualification and progress priorities can be combined in general development procedures, chiefly in low- and internal-profits nations. Evolving information-based and practical climate change strategies require to create science-policy lines through which information makers and politicians unite. Present investigation discloses that co-creation-depend lines conquered neither by information creators nor politicians prosper in enabling the alteration of information into policy. Amphibious vehicle is chiefly defenseless to climate changes that are predictable to source environment destruction and damage and, eventually, resident excisions. But, little is recognized about how the collaboration amongst climate change and destruction may delay the ability of amphibians to adjust to climate change [1]. The approval of movements to alleviate climate change at the domestic level might crowd out following strategy at the general level, which is challenging because state strategy frequently has a larger qualification probable than separate domestic procedures. Climate change attitudes a diversity of pressures to environmental science, biodiversity, and anthropological survives. Mangrove forestry is one of the important countryside-depend explanations that discourse climate change and its influences while providing socio-financial and environmental facilities. With the increasing occurrence of risky weather proceedings, numerous nationwide and resident managements are considering mangrove restoration as a natural protection to these pressures. It measures the cost of mangrove reintegration by directing on the environmental properties and facilities it runs as fine as the rate of the scheme at diverse

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application stages [2]. Forests have been experiencing through enormous compression owing to the components like anthropological events; obtaining of forestry products and climate change which is a main component prompting this compression build up woodlands. Climate change and temperature rise triggered by anthropogenetic events have particularly impacted forests and environment on an international gauge. High temperature rises the soil-water disappearance, ensuing in drier soils, and water loss in forestry vegetation. Corrosion is a foremost form of soil deprivation, with simple significance on gradient constancy and efficiency, and corrosion investigations are essential to forecast probable differences of such singularities, also below climate change situations. Measuring the achievement of climate change variation creativities and outlays needs contemplation of numerous compound proportions that cooperate across period and space a mission that is problematic and occasionally debated. Land usage and climate change impact on water quality and water quantity are well recognized internationally [3].

References

[1] Ahmad, R., Khuroo, A.A., Charles, B., Hamid, M., Rashid, I., Aravind, N.A., 2019. Global distribution modeling, invasion risk assessment and niche dynamics of Leucanthemum vulgare (Ox-eye Daisy) under climate change. Sci. Rep. 9, 1-15. https://doi.org/10. 1038/s41598-019-47859-1.

[2] Alzheimer's Association, 2020. alzheimer's disease facts and figures. Alzheimer's Dementia 16 (3), 391-460.

[3] Power, M.C., Adar, S.D., Yanosky, J.D., Weuve, J., 2016. Exposure to air pollution as a potential contributor to cognitive function, cognitive decline, brain imaging, and dementia: a systematic review of epidemiologic research. Neurotoxicology 56, 235-253.

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ARTICLE

Impact of Compaction Mode on Strength Properties of Sustainable Asphalt Concrete

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ABSTRACT

Various modes of compacting the asphalt concrete mixture can create mechanically different behaviour of the prepared specimens and can alter its sustainability. An attempt has been made in the present assessment to prepare asphalt concrete specimens by implementation of three modes of compaction, the gyratory, the roller, and the Marshall hammer. The specimens were prepared at the target bulk density of Marshall method at optimum asphalt content. Extra specimens were prepared at 0.5 % asphalt below and above the optimum. Core specimens have been obtained from the roller compacted slab samples. The specimens were tested for the Marshall stiffness, tensile, and shear strength. It was observed that at optimum asphalt content, the indirect tensile strength declines by (18.8 and 70.5) % for gyratory and roller compacted specimens respectively as compared with hammer compacted specimens. At optimum asphalt content, the shear strength declines by (70.5 and 82.2) % while Marshall stiffness declines by (10.2 and 44.8) % for hammer and roller compacted specimens as compared with that of gyratory compacted specimen. Specimens prepared by gyratory compaction are less susceptible to the change in the testing temperature as compared with other modes of compaction. It is recommended to consider the mode of compaction to suit the required design property of sustainable asphalt concrete mixture.

1. Introduction

Construction of laboratory asphalt concrete samples is usually intended to simulate the same characteristics as that of the field pavement so that a sustainable mixture can be obtained. However, different laboratory compaction methods can produce samples with different distributions and orientations of shapes of voids and aggregate particles as addressed by Hartmán et al. [1]. The influence of various laboratory compaction procedures (Marshall, vibrating hammer, roller, and gyratory) on the fatigue properties and indirect tensile stiffness of bituminous mixtures was investigated. It was observed that the lower stiffness specimens were produced by

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roller compaction method. The impact of the compaction methods on the fatigue strength of asphalt concrete mixtures is considered as mixture dependent. Asphalt concrete mixtures with grading profiles that are designed for aggregate interlock were found to have higher fatigue strengths, provided that the materials were compacted with the aid of a method that could facilitate reorientation of the aggregate particles. Vacková et al. [2] revealed that insufficiently compacted asphalt concrete layers are more susceptible to more intensive asphalt oxidation and deeper water penetration which aids to faster surface degradation. However, the excessively compacted asphalt pavements are more susceptible to low-temperature cracking and permanent deformations. It was reported that the mode of compaction of asphalt concrete is a significant factor which enhance the strength properties, durability, and resistance to cracking. Specimens were compacted using different compaction energies for evaluating the influence of poor compaction on the asphalt concrete properties. The specimens were compacted by Marshall hammer with different amounts of blows. The stiffness modulus at four testing temperatures was measured. The result exhibits very strong dependence between compaction rate and decrease of stiffness modulus. Huang et al. [3] constructed asphalt concrete test sections of pavement by implementing static, vibratory, and semi-static-vibratory rolling at various compaction repetitions. The effects of the rolling methods in the field, cooling time, and compaction numbers on asphalt concrete pavement were investigated. It was revealed that, if the asphalt concrete pavement is opened to traffic and the strength development and stability of asphalt concrete are simultaneously considered, the pavement should first be compacted with the aid of vibratory rollers, followed by static rollers to complete the construction of the pavement. Xing et al. [4] stated that the number of contact points, structure of the aggregate, and orientation of the aggregate particles is dependent on the conditions and compaction methods. Correlations between the obtained strength results and compaction methods were observed. The strength of the asphalt concrete is directly related to its compaction process, which can significantly affect the overall properties of the asphalt mixture. It was concluded that the difference in strength may be related to the change in aggregate interlock pattern in the specific compaction method. Airey and Collop [5] revealed that the laboratory compaction methods can differ in many parameters, such as the compaction time, the pressure force and the way the force is transmitted, and the final shape of the obtained asphalt concrete sample and the aggregate particles orientation inside. Marcobal et al. [6] assessed three laboratory compaction methods (Marshall impact hammer, gyratory compactor, and static load) and defined the most suitable compaction testing technique for asphalt mixtures. The mechanical characteristics of the asphalt mixture performance was conducted to quantify the stiffness modulus, Indirect Tensile Strength (ITS), four-point bending fatigue, and rutting test. Mixtures with 100 % Reclaimed Asphalt Pavement (RAP) and emulsified bitumen exhibited proper mechanical and volumetric behavior in terms of rutting resistance, moisture damage, fatigue cracking, ITS, stiffness modulus. Tarefder and Ahmad [7] assessed the structure of asphalt concrete compacted by linear kneading compactor, gyratory compactor, and field cores. The variations of moisture damage and permeability of samples prepared by various compaction procedures were compared. It was noticed that the structure of field compacted asphalt concrete samples is totally different from gyratory compacted and linear kneading compacted asphalt samples. The indirect tensile strength of field samples is always less than gyratory samples and more than linear kneading compacted samples. Linear kneading compacted samples and field samples are shown to be more susceptible to moisture than the gyratory compacted samples. Woszuk and Franus [8] revealed that under the laboratory conditions, specimens of asphalt concrete can be compacted in different ways, depending on type of tests, the type of technology used, the purpose of the sample, and the applicable regulations. The most used devices are Marshall compactor, gyratory compactor, vibrating compactor, and asphalt roller compactor. Radzi et al. [9] stated that the laboratory compaction for asphalt concrete specimen compaction and fabrication is expected to simulate the properties of the asphalt concrete pavement in the field. It is desirable that the laboratory compaction of asphalt concrete specimens should be a true indicator of field performance of the mixture regarding air voids content, particle orientation, permeability, and mechanical properties. Pérez-Jiménez et al. [10] revealed that the influence of compaction procedures using Marshall compactor and Superpave gyratory compactor on mechanical and volumetric properties of asphalt mixture indicated that it is not wise to set up several gyrations to compact the asphalt concrete specimens with a target bulk density that is like to the obtained one through Marshall compaction technique because the number of loading cycles varies depending on the asphalt mixture type. Cheung and Dawson [11] addressed that the general aggregate structure and the aggregate particles orientation are significantly different in specimens compacted by various methods. The roller compacted asphalt concrete

slab samples are characterized by the aggregate particle size distribution across. However, the samples produced using other laboratory compaction methods of specimens in the mold are susceptible to circumferential particle orientation. Interlocking and contact of aggregates, based on the shape of the aggregate, also has a significant impact on the compaction. Using angular aggregate particles leads to exhibit more uniform distribution of aggregates contact points and internal forces, with a better interconnection between elements and improvement to permanent deformation and fatigue performance resistance. Wróbel et al. [12] revealed that the under-compacted asphalt concrete mixes are characterized by their lowest stiffness modulus and lowest indirect tensile strength regardless of the test temperature. The indirect tensile strength ratio was the lowest for those asphalt concrete samples, which confirms that the insufficiently compacted asphalt layers could be more susceptible to water and frost. The increased air voids content due to lower compaction can cause premature degradation of the asphalt concrete pavement. However, over-compaction is particularly dangerous. There may cause loosening of the aggregate and damage to their contact points, which can result in reduced resistance to the weathering and can lead to the destruction of the road surface. Reduction in the strength and the stiffness for over-compacted specimens could be detected.

The aim of the present investigation is assessing the influence of three modes of compaction namely (Marshall, gyratory, and roller) on the strength properties (punching shear strength, indirect tensile strength, and Marshall stiffness) of the asphalt concrete mixtures prepared at three various percentages of asphalt binder by weight of aggregates. Consideration of the mode of compaction to suit the required design property can support obtaining a sustainable asphalt concrete mixture.

2. Materials Characterizations

The materials used in the present investigation are usually used by roadway agencies for asphalt pavement construction in Iraq.

2.1 The Asphalt Cement Binder

The asphalt binder used in this investigation has a penetration grade of 40-50. It was obtained from Dourah oil refinery. Physical properties of the asphalt cement are listed in Table 1.

2.2 The Fine and Coarse Aggregates

The crushed coarse aggregates which has a nominal maximum size of 12.5 mm were obtained from AL-Nibae quarry, the fine aggregates are also obtained from the same source. A typical dense gradation as per the State Commission for Roads and Bridges, SCRB [14] usually implemented for wearing course layer was employed. The physical properties of the fine and coarse aggregates are listed in Table 2.

Table 1. The Physical properties of Asphalt Binder according to ASTM [13]

Property	Testing conditions	ASTM Designation	Test results
Penetration	25° C, 100 gm.,5 Seconds, (1/10 mm)	D 5	41
Softening point	Ring and ball	D 36	49
Ductility	25 ° C, 5 Cm/minutes	D 113	+ 150
Specific gravity	25 ° C	D 70	1.01
Flash point	Cleveland open cup	D 92	275

Table 2. The Physical properties of coarse and fine aggregates according to ASTM [13]

Physical properties	Coarse aggregates		Fine aggregates	
	ASTM Designation	Test results	ASTM Designation	Test results
Bulk specific gravity	C 127	2.584	C 128	2.604
Apparent specific gravity	C 127	2.608	C 128	2.664
Water absorption %	C 127	0.57	C 128	1.4
Wear - Los Angeles abrasion %	C 131	13.0	------	-------

2.3 The Mineral Filler

Ordinary Portland cement was obtained from Tasluga cement plant and implemented as mineral filler; the physical properties of the mineral filler implemented are listed in Table 3.

Table 3. The Physical properties of the filler

Property	Test results
Specific gravity	3.14
Specific surface area (m^2/kg)	355
Percent passing sieve No. 200	96

2.4 Selection of Asphalt Concrete Aggregates Gradation

Asphalt concrete with dense gradation is usually used for wearing course as per State Commission for Roads and Bridges SCRB [14] specification. The aggregates which have 12.5 mm nominal maximum size has been implemented. Table 4 exhibits the selected aggregates

gradation and the SCRB [14] specification limits.

Table 4. Combined Gradation of Aggregates for Wearing Course as per SCRB [14]

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.3	0.75
Selected aggregates gradation	100	95	83	59	43	13	7
SCRB, [14] Specification limits	100	90-100	76-90	44-74	28-58	5-12	4-10

3. Testing Methods

3.1 Preparation and Compaction of Asphalt Concrete Specimens by Marshall Hammer Method

Fine and Coarse aggregates were combined with the required amount of filler to meet the SCRB, [14] specification for wearing course. The combined aggregates were heated to 160 °C while the asphalt binder was heated to 150°C. The combined aggregates and asphalt binder were mixed thoroughly until the aggregates get coated with thin film of the asphalt binder and were ready for the compaction process. The compaction process starts after pouring the hot mix asphalt concrete into the Marshall mold of 63.5 mm in height and 101.6 mm in diameter. The mixture was subjected to 75 blows of the Marshall hammer on each side of the specimen. The compacted specimens were left to cool at laboratory environment for 24 hours then the specimens were extruded from the mold. Specimens were prepared at optimum binder content of 4.7 % and at 0.5 % asphalt below and above the optimum binder requirements. Specimens were subjected for strength properties determination such as Marshall stiffness which was calculated by dividing the Marshall stability in (kN) by Marshall flow in (mm), indirect tensile strength ITS (kPa), and double punching shear strength (kPa). Details of obtaining the optimum binder content could be referred to Sarsam and Al-Obaidi [15]. Specimens were tested in triplicate and the average value of each strength test was considered for analysis.

3.2 Preparation and Compaction of Asphalt Concrete Specimens by Gyratory Compaction Method

The Gyratory compaction technique was adopted to prepare the required asphalt concrete specimens at the target density of the Marshall specimens for the three percentages of asphalt binder. Specimens were prepared using (148) gyrations, which was obtained after many trials. The procedure for preparation of asphalt concrete mixtures was as that of Marshall mixtures. The mold with the asphalt mixture was assembled into the Gyratory compactor machine and centered under the loading ram. The gyrations starts and the ram extends down into the mold and touches the specimen. The ram stops when the pressure reaches 600 kPa. After feeding the necessary information concerning the specimen to the software, and implementing the gyration angle of (1.25°), the compaction process of the specimen started. When the specimen reaches the specified height with the design number of gyrations, the compaction process stops automatically. The mold will be discharged from the device. The specimen with 63.5 mm in height and 101.6 mm in diameter is extracted from the mold and left to cool at room temperature for 24 hours. Specimens were prepared at optimum binder content of 4.7 % and at 0.5 % asphalt below and above the optimum. Specimens were subjected for strength properties determination such as Marshall stiffness which was calculated by dividing the Marshall stability in (kN) by the Marshall flow in (mm), indirect tensile strength ITS (kPa), and double punching shear strength (kPa). Details of the gyratory compaction trials could be found at Sarsam and Al-Obaidi [16]. Specimens were tested in triplicate and the average value of each strength test was considered for analysis.

3.3 Preparation and Compaction of Asphalt Concrete Specimens by Roller Compaction Method

Based on the target density of Marshall specimens and its asphalt content, the required mixture weight was heated to 165 ° C, then transferred to the roller compaction mold of (300 x 400 x 70) mm size and subjected to roller compaction. The applied load was 5 kN, and the required number of rollers passes to achieve the required target density was 56 which was obtained after many trials as per EN 12697 - 33, [17]. The slab samples were rejected from the roller compactor and removed from the mold after 24 hours. Core specimens of 63.5 mm in thickness and 101.6 mm in diameter were extracted from the slab samples. Specimens were prepared at optimum binder content of 4.7 % and extra specimens were prepared at 0.5 % asphalt below and above the optimum binder content. Specimens were subjected for strength properties determination such as Marshall stiffness which was calculated by dividing the Marshall stability in (kN) by the Marshall flow in (mm), the indirect tensile strength ITS (kPa), and the double punching shear strength (kPa). Specimens were tested in triplicate and the average value of each strength test was considered for analysis. Details of the trial samples and optimization of the rolling process could be referred to

Sarsam and Khalid [18].

3.4 Testing of Asphalt Concrete Specimens

The prepared asphalt concrete specimens by the aid of the three modes of compaction were tested for Marshall Stability and flow value at 60°C as per ASTM, 2016, double punching shear strength at 60°C As per Jimenez, [19], and indirect tensile strength at (60, 40, and 25) °C as per ASTM [13]. Table 5 demonstrates the design bulk density implemented for preparing the asphalt concrete specimens for each asphalt binder content.

Table 5. The Implemented Bulk density for Asphalt Concrete

Asphalt binder content %	Bulk dry density gm/cm^3
4.2	2.310
4.7	2.350
5.2	2.362

4. Results and Discussions

4.1 Influence of Compaction Mode on Indirect Tensile Strength

Figure 1 demonstrates the influence of compaction mode and binder content on the Indirect Tensile Strength ITS of asphalt concrete when tested at 25 °C. It can be noticed that the roller compaction mode exhibits the lowest tensile strength regardless of the binder content as compared with other modes of compaction. This may be attributed to the orientation of aggregate particles and non-restriction on the movement of particles in the horizontal direction. Such behavior agrees with Xing et al. [4]. However, Marshall hammer compaction exhibits the highest tensile strength. This could be attributed to the restricted movement of aggregate particles within the mold. The highest tensile strength was obtained at optimum binder content of 4.7 % regardless of the compaction mode. The tensile strength of asphalt concrete declines when the binder content increases or decreases by 0.5 % than the optimum by (16.3 and 18.4) %, (6.9 and 0.6) % and (4.7 and 23.6) % for hammer, gyratory and roller compacted mixtures respectively. On the other hand, the tensile strength of asphalt concrete prepared at optimum asphalt content, declines by (18.8 and 70.5) % for gyratory and roller compacted specimens respectively as compared with that of hammer compacted specimens. Similar behavior was reported by Tarefder and Ahmad [7].

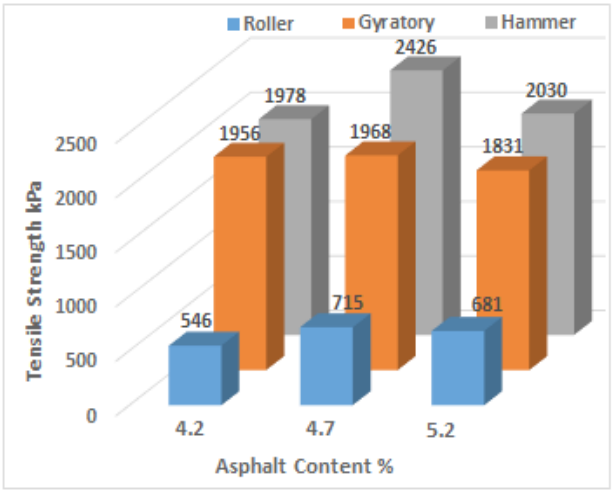

Figure 1. Influence of Binder Content on Tensile Strength

4.2 Influence of Testing Temperature and Compaction Mode on Indirect Tensile Strength

Figure 2 exhibits the influence of testing temperature on the indirect tensile strength of asphalt concrete specimens prepared with three modes of compaction. It can be observed that specimens prepared by gyratory compaction are less susceptible to the change in the testing temperature as compared with other modes of compaction. The tensile strength of asphalt concrete declines by (93.8, 61.8, and 78.1) % for hammer, gyratory, and roller compacted specimens respectively when tested at 60 °C as compared to the case of testing at 25 °C. Such finding agrees with Sarsam S. and Khalid [18].

4.3 Influence of Compaction Mode on Double Punch Shear Strength

Figure 3 exhibits a significant variation in shear strength of asphalt concrete upon modes of compaction. It can be detected that as the binder content increase, the shear strength increases regardless of the compaction mode. This may be attributed to the fact that the asphalt mixture was designed based on Marshall method. The selected optimum binder content is selected based on the average of (maximum density, stability, and average voids content). Such optimum binder percentage may not satisfy the shear stress requirements. More binder seems to be required for lubricating the aggregate particles through the various modes of compaction to satisfy the shear requirements. The shear strength increases by (0.8 and 3.2) %, (12.1 and 39.3) %, and (3.8 and 27.1) % when the binder content rises from(4.2 to 4.7 and 5.2) % for gyratory, hammer, and roller compacted specimens

respectively. At optimum asphalt content, the shear strength declines by (70.5 and 82.2) % for hammer and roller compacted specimens as compared with that of gyratory compacted specimen. Such finding agrees with Al-ammari et al. [20].

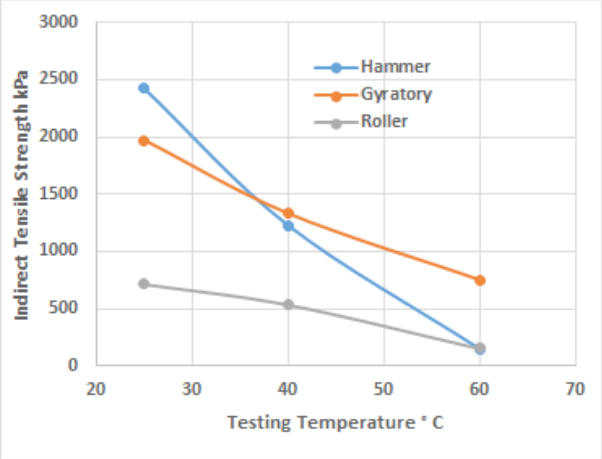

Figure 2. Influence of Testing Temperature on Tensile Strength

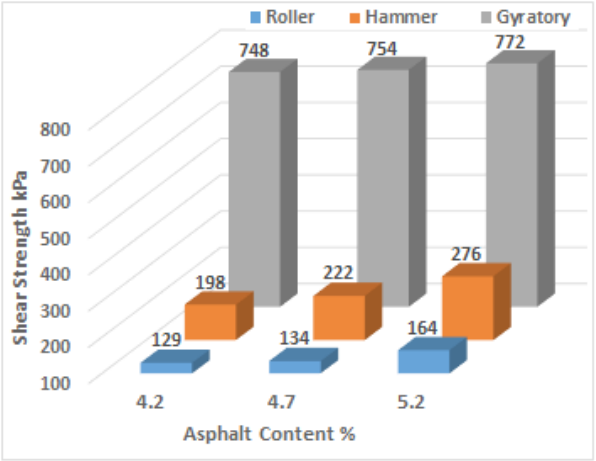

Figure 3. Influence of Binder Content on Shear Strength

4.4 Influence of Compaction Mode on Marshall Stiffness

Figure 4 demonstrates the variation in Marshall stiffness which was calculated by dividing Marshall stability in (kN) by the flow value in (mm) among compaction modes at various binder percentages.

It can be detected that gyratory compaction exhibits the highest Marshall stiffness among other modes of compaction. However, the optimum binder content exhibits the highest Marshall stiffness regardless of the compaction modes. The Marshall stiffness of asphalt concrete declines when the binder content increases or decreases by 0.5 % than the optimum by (4 and 6.1) %, (18.1 and 13.6) % and (7.4 and 11.1) % for hammer, gyratory and roller compacted mixtures respectively. At optimum binder content, Marshall stiffness declines by (10.2 and 44.8) % for hammer and roller compacted specimens as compared with that of gyratory compacted specimen. Such behavior agrees with the work which was reported by Wróbel et al. [12].

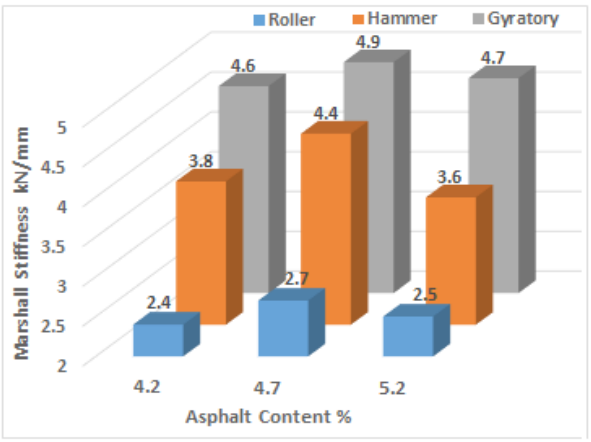

Figure 4. Influence of Binder Content on Marshall Stiffness

5. Conclusions

Based on the limitations of materials and the testing program implemented, the following conclusions may be addressed:

The indirect tensile strength of asphalt concrete declines when the binder content increases or decreases by 0.5 % than the optimum by (16.3 and 18.4) %, (6.9 and 0.6) % and (4.7 and 23.6) % for hammer, gyratory and roller compacted mixtures respectively. The shear strength increases by (0.8 and 3.2) %, (12.1 and 39.3) %, and (3.8 and 27.1) % when the binder content rises from(4.2 to 4.7 and 5.2) % for gyratory, hammer, and roller compacted specimens respectively. The Marshall stiffness of asphalt concrete declines when the binder content increases or decreases by 0.5 % than the optimum by (4 and 6.1) %, (18.1 and 13.6) % and (7.4 and 11.1) % for hammer, gyratory and roller compacted mixtures respectively. However, specimens prepared by gyratory compaction are less susceptible to the change in the testing temperature and exhibit higher shear strength and Marshall stiffness as compared with other modes of compaction. On the other hand, specimens prepared by Marshall hammer compaction exhibit higher tensile strength as compared

with other modes of compaction. It is recommended to consider the mode of compaction to suit the required design property of sustainable asphalt concrete mixture.

References

[1] Hartmán, A.; Gilchrist, M.; Walsh, G. (2001). Effect of mixture compaction on indirect tensile stiffness and fatigue. J. Transp. Eng. 127, 370-378.

[2] Vacková P., Valentin J., Kotoušová A. (2018). Impact of lowered laboratory compaction rate on strength properties of asphalt mixtures. Innovative Infrastructure Solution ;3: P.1-8. http://doi:10.1007/s41062-017-0111-6.

[3] Huang L., Lin D., Luo H., Lin P. (2012). Effect of field compaction mode on asphalt mixture concrete with basic oxygen furnace slag. Construction and Building Materials. Volume 34, September. P. 16-27, Elsevier. https://doi.org/10.1016/j.conbuildmat.2012.02.008.

[4] Xing, C.; Xu, H.; Tan, Y.; Liu, X.; Ye, Q. (2019). Mesostructured property of aggregate disruption in asphalt mixture based on digital image processing method. Constr. Build. Mater. 200, P. 781-789. https://doi.org/10.1016/j.conbuildmat.2018.12.133.

[5] Airey G., Collop A. (2014). Mechanical and structural assessment of laboratory and field-compacted asphalt mixtures. Int. J. Pavement Eng. 17: P. 50-63. http://doi:10.1080/10298436.2014.925551.

[6] Marcobal J., Lizárraga J., and Gallego J. (2019). Laboratory compaction study and mechanical performance assessment of half-warm mix recycled asphalt mixtures Containing 100% RAP. Materials. 12, MDPI, 1992.
DOI: 10.3390/ma12121992 www.mdpi.com/journal/materials.

[7] Tarefder, R.A.; Ahmad, M. (2016). Effect of compaction procedure on air void structure of asphalt concrete Measurement, 90, P. 151-157. https://doi.org/10.1016/j.measurement.2016.04.054.

[8] Woszuk A., Franus W. (2016). Properties of the Warm Mix Asphalt involving clinoptilolite and Na-P1 zeolite additives. Constr. Build. Mater. 114: P. 556-563. http://doi:10.1016/j.conbuildmat.2016.03.188.

[9] Radzi H., Muniandy R., Hassim S., Lawand T., Jakarni F. (2019). An overview of asphalt mix designs using various compactors. IOP Conf. Ser.: Mater. Sci. Eng. 512 012031. http://doi:10.1088/1757-899X/512/1/012031.

[10] Pérez-Jiménez F, Martínez A, Miró R, Hernández-Barrera D and Araya-Zamorano L. (2014). Effect of compaction temperature and procedure on the design of asphalt mixtures using Marshall and gyratory compactors Construction and Building Materials 65 264-9.

[11] Cheung L.W., Dawson A.R. (2002). Effects of Particle and Mix Characteristics on Performance of Some Granular Materials. Transp. Res. Rec. J. Transp. Res. Board. 1787: P. 90-98. http://doi:10.3141/1787-10.

[12] Wróbel M., Woszuk A., and Franus W. (2020). Laboratory Methods for Assessing the Influence of Improper Asphalt Mix Compaction on Its Performance. Materials (Basel). MDPI. Jun; 13(11): 2476. http://doi:10.3390/ma13112476.

[13] ASTM, American Society for Testing and Materials, ASTM: (2016). Road and Paving Material, Vehicle-Pavement System, Annual Book of ASTM Standards, Vol. 04.03. www.astm.org.

[14] SCRB. (2003). State Commission of Roads and Bridges. Standard Specification for Roads & Bridges, Ministry of Housing & Construction, Iraq.

[15] Sarsam, S.I.; Al-Obaidi, M.K. (2014). Assessing the Impact of Various Modes of Compaction on Tensile Property and Temperature Susceptibility of Asphalt Concrete. Int. J. Sci. Res. Knowledge. 2, P. 297-305.

[16] Sarsam S. and Al-Obaidi M. (2014). Modeling the Impact of Various Modes of Compaction on Shear Property of Asphalt Concrete. Research Journal of modeling and simulation, (RJMS) Vol.1 No. (4), pp. 56-64, Sciknow publication Ltd. USA.

[17] EN. EN 12697 - 33, (2007). Bituminous Mixtures - Test Methods for Hot Mix Asphalt - part 33: Specimen prepared by Roller Compactor, European Committee for Standardization.

[18] Sarsam S. and Khalid M. (2016). Influence of compaction method on asphalt concrete quality. Lambert academic publishing, ISBN: 978-3-330-02415-1.

[19] Jimenez, R. A. (1974). Testing for Debonding of Asphalt from Aggregates, Transportation Research Record 515, TRB, National Research Council, Washington, D.C., P. 1-17.

[20] Al-ammari M., Jakarni F., Muniandy R., and Hassim S. (2019). The effect of aggregate and compaction method on the physical properties of hot mix asphalt. IOP Conf. Ser.: Mater. Sci. Eng. 512 012003 https://www.researchgate.net/publication/332622467.

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ARTICLE

Strength & Conduct of Reinforced Concrete Corner Joint under Negative Moment Effect

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ABSTRACT

The aim of our study is to reveal the effect of steel reinforcement details, tensile steel reinforcement ratio, compressed reinforcing steel ratio, reinforcing steel size, corner joint shape on the strength of reinforced concrete Fc' and delve into it for the most accurate details and concrete connections about the behavior and resistance of the corner joint of reinforced concrete, Depending on the available studies and sources in addition to our study, we concluded that each of these effects had a clear role in the behavior and resistance of the corner joint of reinforced concrete under the influence of the negative moment and yield stress. A study of the types of faults that can be reinforced angle joints obtains details and conditions of crushing that are almost identical for all types of steel reinforcement details and the basic requirements for the acceptable behavior of reinforced concrete joints in the installations and the efficiency of the joint and this may help us to prepare for disasters, whether natural or other, as happens with tremors The floor and failure that may occur due to wrong designs or old buildings and the possibility of using those connections to treat those joints and sections in reinforced or unarmed concrete facilities to preserve the safety of humans and buildings from sudden disasters and reduce and reduce risks, as well as qualitative control over the production of concrete connections and sections free from defects to the extreme.

1. Introduction

In many structures, the continuity of two adjacent sides is necessary even if it is related to an angle. The link resulting from this confluence is expressed as the angle compass. Concrete corner joints are found in many different structures such as retaining walls, bridges and building structures. They are also found in hydraulic structures such as ground and elevated reservoirs (flumes) and culverts.The design of the straight ribs meeting at the junction can be carried out by any structural engineer, while the information is incomplete about the design of the junction area in which the moments are greatest relative to the junction and that the sudden change in the

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direction of the ribs generates high local stresses as shown in Figure 1 and 2.

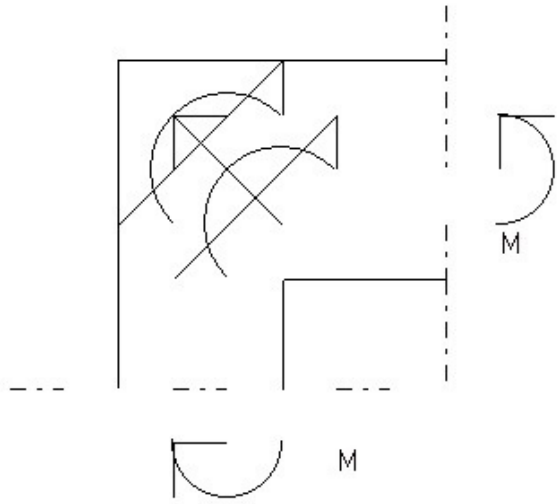

Figure 1. Tensile stresses at sections perpendicular to the diameter of the joint

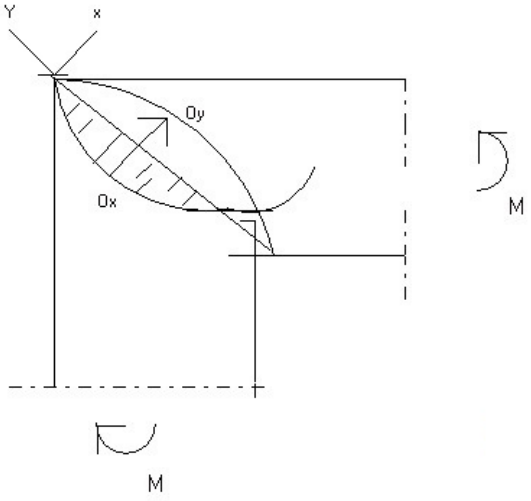

Figure 2. Diagonal stresses of an angle joint subjected to a positive torque

Surprisingly, until recently, little attention has been paid to design angle joints in reinforced concrete structures. After 1965 this situation changed and there was a wide interest in studying this point. The reason for this change was conducting a preliminary study in Sweden on an angle connection in the bridge supports. This study proved that the reinforcement details were not designed correctly, causing failure at one third of the design value. These details were lacking in Sweden and in other parts of the world at that time. Numerous experiments were conducted to find alternative rebar details of good efficiency.The researchers conducted tests on all types of armaments that were known at that time and noticed that most of them were inefficient.

The difference in the details of the rebar and the angle of the joints are important factors that affect the final value of the joints as well as affect the efficiency of the joints. The difference in the size of the joint is another factor that greatly affects the final critical value of the joints. These previous factors were not considered in the design. Corners may be subjected to closing moments, which are subject to tensile stresses at the outer corner of the corner, or opening moments, which cause tensile stresses at the inner corner. The latter kind of moment may cause more detailed problems. Opening joints can be found in water tanks with retaining walls, open channels, bridge abutments, high elevations due to the influence of wind, frame structures, etc., on the other hand, the closing joint can be found in hinged and fixed frames and underground water tanks.

Accordingly, the researchers are interested in opening the angle continued their research in an attempt to improve the efficiency of the available reinforcement details, while the researchers interested in closing the angle focused their efforts to find ways to design the joint as a single unit. To study the shear strength of the junction. In another study by [1] on the effect of using (FILLET) at the inner corner of the joint or cutting the inner corner as shown in Figure 3 and 4 on the resistance and behavior of the joint. Pressure steel reinforcement. [1] also studied the effect of pressure steel reinforcement.

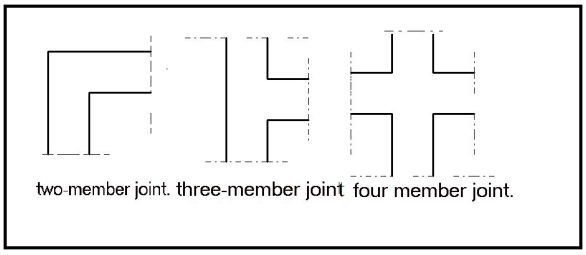

Figure 3. Types of beams column joint

They confirmed the results were presented for an experimental program previously related to the effect of reinforcement on the behavior of the angles exposed to the load at the moment of opening [2]. The reason behind this is the damages observed in the coalmine. Three full-size samples were tested with different types of reinforcement in the joint. The first sample has characteristics similar to the current structure. The other two samples were visualized and tested respectively, and each was detailed according to the observations made during the testing of the previous sample. The failure method and the reinforcing strains that were measured in each case are

discussed.

Explored the effects of slab corners on torsional behavior of circumferential beams in buildings with reinforced concrete beams [3], especially in the case of column loss. Several torsional tests have been carried out on the end beams, and a comparison has been made with and without ceilings ,Subsequently, physics-based numerical models were developed, based on the test results, to verify the effect of changing slab parameters, such as thickness and strength ratio, on torsional capacitance. The samples have shown that the presence of reinforced concrete slabs can increase the torsional strength of the circumferential beams by the same amount to 97%. The improvement came first from the angle of the slab, which was a set of compressive struts. And this effect increases with increasing thickness of the slab. It has also been observed that the angles of the plates tend to offset the torsional failure (which occurred at the twisted beam near the armature) to approximately one beam depth. The negative contribution is likely to lead at the bending moment to strengthen the slab along the edges and enhance the overall structural strength.

Concluded in their empirical and analytical study on the effect of reinforcement details [4], confining, joint size, and joint angle on the efficiency of frame joints, and the comparison between closed and open joints. Experimentally, samples were tested for a total of 11 samples under the influence of vertical load. All samples were tested to failure and behavior was fully monitored. In addition, a nonlinear analysis of the 3D finite elements was generated using ABAQUS software and the experimental results were verified to give design recommendations for those structural element.

The structural behavior of simple structural members such as beams and columns is usually fixed in traditional designs but on the other hand, the details, strength and behavior of corner joints, especially those subject to opening moments as in the case of cantilever supporting walls, bridge abutments, ducts, cabinet structures and gate frames, are not specified, Detailed and final. Corner reinforcement details may play a major role in influencing the structural behavior of a joint further if joints or corners are opened.

Few studies have been done on frame joints to determine joint details, which may serve the purpose of strength requirements, limited cracking, ductility and simplicity of construction, and these details may vary from code to code.

The rebar must be laid in such a way that the joints perform the basic requirements. The joint must be able to withstand the calculated failure in its adjacent cross sections, because it does not limit the bearing capacity of the frames. Also, the rebar scheme in the joint must contain the necessary flexibility, so that The force can be redistributed without brittle failure in the joints, the width of the kerf at the corner must be limited to acceptable values of the working load level, and the rebar parts must be easy to manufacture.

The failure of the reinforced concrete joint may be due to several reasons such as bevel tension crack, split fracture, failure when producing steel reinforcement, failure due to concrete cracking and installation failure.

It is found that Rebar sections stipulated in the then Swedish regulations for the design of frame corners in concrete civil defense shelters are rather complex which makes it difficult to implement them correctly [5]. Therefore, a simpler method was developed, according to which all reinforcing bars are cut inside the corner area. The aim of his study was to evaluate a new design proposal and to determine whether it would be appropriate to replace traditional steel rebar sections with the new type. Eight full-scale tests were conducted for tire angles subject to negative critical moment (angle closing). The parameters differed in the tests which are the details of the rebar, the ratio of the reinforcement, the type of reinforcement and the composition of the reinforcing bars. Finite element analyzes, with material models based on nonlinear fracture mechanics and plasticity, have been performed for frame angles with new and traditional rebar detailing. The effects and weakness of the masonry joint, the interaction between the reinforcement and concrete, and the mechanical properties of the rebar were also investigated using this method. It was estimated that tests and analyzes showed that the details of conventional and new steel rebars for practical purposes are equivalent when using a low reinforcement ratio; They note that this is also the case when a high booster ratio is used. Accordingly, this work supports the idea that the new detail is suitable for use in place of traditional rebar detailing. The analyzes showed that the bond slip relationship affects the rigidity of the structure and that it also affects the overall deformation capacity. However, its effect on the maximum load capacity was found to be minimal. Moreover, it has been shown that the mechanical properties of rebar can have a significant influence on the deformation ability; After the initial cracking, the weakness of the masonry joint has little effect on the structural behavior of the tire angle.

Found in their experimental study and laboratory tests of both strength and behavior in obtuse angles of reinforced concrete under the bending holes of five of the thirteen total samples with an obtuse angle of 145 degrees

[6], the tested corner samples had different reinforcement details; in the rest of the thickness or length of each of the adjacent members which were Various patterns of observed crack and failure and absolute strengths adding inclined bars to rings at joints have been found to significantly improve bending efficiency. The effect was to change the hardness, Neighboring members have a role in greatly improving efficiency and as a result gradual change in the prevailing and traditional methods of failure.

Studied special samples using glass fiber reinforced polymers as the main reinforcement in concrete structures [7]; he found an attractive option for structures in aggressive environments. In his study, he emphasized that the concrete knee joints are joints where the crossbar and the column end at the joint. The application of GFRP bracing in the knee joints may be problematic given the weak link at the reinforcing curve. This is critical because there is a risk of possible premature joint failure due to penile rupture, regardless of adjacent organ designs. The behavior of GFRP-reinforced knee joints has not been studied before. The presented experimental program consisted of eight full-size samples that were tested under monotonous sealing loads. The variables that have been studied are the effect of varying reinforcement ratio, the effect of confinement stirrups in the joint, and the effect of angle geometry. The eight samples are divided into two groups, confined and unconfined samples. Of the eight samples, two were designed with variable geometry to include the internal chamfer. The test results indicate that the increase in the reinforcement ratio improves the force efficiency while changing the failure mode directly: failure due to rupture of the rod is prevented with the increase in the reinforcement ratio and is caused by the failure of the inclined bracket. The addition of a confinement stirrup increased the absolute force as well as the maximum deflection. The effect of changing the angle geometry has a slight effect on the strength of the sample; However, brittle failure of the joint was prevented. Further studies are to be conducted including different confinement techniques, different FRP types and suppliers, as well as different types of loading such as opening moments and load reflections.

In their study [8] found Frames are used in special critical moments of reinforced concrete as part of seismic strength resistance systems in designed buildings to resist earthquakes. Beams, columns and beam-column joints Moment tires are proportional and detailed for resistance, bending, axial and shear actions produced as a building, Oscillates through multiple displacement cycles during force earthquake, earthquake. Special proportion and Details of requirements lead to a tire that can resist Strong earthquake shaking without significant loss of hardness or strength. These moment-resistant tires are called "Special Moment tires" due to these additional requirements, which improves seismic resistance compared to less, finely detailed medium and regular moment frames. The concepts of rebar for tires at the crucial special moment are concrete It was introduced in the United States beginning around 1960 (Bloom, Newmark, and Corning 1961). Its use at that time was mainly in Designer appreciation of installations, as it was not until 1973 that The Uniform Building Code (ICBO 1973) first requires the use of Special frame details in areas with high seismicity. The Closer to detail requirements are remarkably similar to those In place today.

They began their studies [9] as a core part of a collaborative project aimed at (NEES-Grand Challenge) that aims to assess collapse risks and develop mitigation strategies for older type RC buildings. The behavior of unreinforced joints under earthquake loads was of interest in this study, and they conducted extensive analytical and experimental investigations to simulate the gradual collapse of old RC buildings and create fragile collapse curves.

This study describes an experimental program that develops instantaneous rotation; the relationships are similar to the backbone relationships of unreinforced joints for simulations of sub-assemblies of beam columns and prototype building frames. To predict the shear strength, two models of shear strength have been developed by quasi-experimental and analytical approaches, and a new working model has been developed. Four full-scale testing and unreinforced concrete angle joint samples were performed to verify proposed shear strength models and to provide standard information for the development of unreinforced backbone relationships for external joints. The evolving spinal relationships were validated by accurate reproduction of the load displacement responses of four external joint samples and four other planar samples, and the external joint samples were taken from the literature. As an introduction to progressive breakdown analysis. For older type RC buildings, nonlinear dynamic simulations were performed on three virtual building frameworks using the developed backbone relationships.

A. Resistance requirements for concrete structural buildings and requirements for buildings and structures resistant to earthquake loads:

Seismic loads (and horizontal loads in general) can be resisted by a number of structural systems. Among these structural systems, the following systems can be

mentioned:

1) Frame System

This system consists of columns and beams connected to each other by rigid joints, meaning joints that bear a bending moment. This system is made of steel (steel) or reinforced concrete. And the reinforced concrete frame must be ductile to secure large deformations before collapsing to dissipate or reduce the energy of the earthquake and make the collapse (if it occurs) safe.

2) Wall system

This system consists of vertical load bearing walls. These walls can be executed from built stones (or from non-reinforced materials in general), and the connection of the wall with the ceiling in this case is hinged joints, and these load-bearing walls can also be executed from reinforced concrete, and the connection of the wall with the ceiling in this case With rigid compasses, the wall in this case is called a shear wall.

3) Mixed systems of frames and shear walls

This system comprises a group of frames and another group of shear walls, which together share in resisting horizontal loads in their stiffness proportions.

4) Sufficient frame system

This system is made of steel in particular, where the frame system is lined with appropriate elements, after which the frame is transformed into a kind of truss. It can also be implemented from reinforced concrete.

5) Prefabricated Establishments System

This system consists in particular of panels in the form of load-bearing walls and other panels that are placed horizontally and act as slabs, and this system is usually implemented from prefabricated reinforced concrete. The connection between the wall panels and the slab panels in this system is by hinged joints practically that cannot withstand bending moments. The load-bearing walls in these structures are studied to resist bending moments as cantilever shear walls that operate vertically with the condition that they do not have any tensile stresses in any section. In both vertical and horizontal directions.

B-Requirements for buildings that will withstand horizontal loads in the frame system (columns and beams)

It is preferable that the height of the reinforced concrete building not exceed (7) seven floors (floors), including the floors of the basements, if any.

The set of columns that will make up the frame should lie on one straight line.

The tires shall be shaped according to the previous condition in both directions.It is preferable to use frequent spacing between columns (using the modular reinforced concrete frames)

What is stated in this regard in terms of design requirements and armament details in (the Arab code for the design and implementation of reinforced concrete structures) of the Arab code shall be taken into account.

Columns:

Column design: Column design is prohibited assuming that there are spandex (plastic) joints in them.

Connection: Reinforcing steel joints with columns and beams are implemented in a way that ensures the transmission of bending torques between them according to the requirements of the Arab design code, and for reinforced concrete columns, reinforcing bars are installed in the beams or connections to ensure the durability of the connection.

Reinforced Concrete Columns: Concrete Columns shall be closed. Circular canes (with hooks) are used for circular poles, noting that spiral bracelets can be used to increase resistance.

Elongated frame columns: The length of the frame columns is designed in full compliance with all the requirements stipulated in the Arab code for the design and implementation of reinforced concrete structures from the Arab code.

Horizontal slabs (diaphragms):

1) Rigidity: The horizontal slabs (which act as diaphragms) are rigid within their level, and capable of transferring horizontal forces to the vertical bracing elements without subjecting them to major deformations.

2) Connecting beams (Jizan): The tiles shall be surrounded by connecting beams capable of resisting tensile or compressive forces of no less than (50) kilonewton, according to the safety parameters and requirements for stability and stability stipulated in (the Arab Code for the Design and Implementation of Reinforced Concrete Structures and the Arab Code for Steel Structures) with special care in fixing the reinforcing bars at the corners.

3) Transfer of forces within the slabs: In the event of a sudden change in the vertical stiffening elements, such as the shift in the stiffness of columns or walls, it should be ensured that the forces transfer within the slabs, especially at the level of this change. The connecting beams surrounding these connections must be able to withstand tensile or compressive forces of no less than (100) kilonewtons, and according to the safety factors stipulated in the Arab design codes.

4) Connecting between the tiles and the vertical stapling elements: It should be ensured that solid connections are obtained between the tiles and the vertical stapling elements, by installing the slabs' reinforcing bars

in the vertical stapling elements [9].

2. Methodology

The main objective of conducting finite element analysis as samples is to extend the scope of investigations that have been conducted experimentally in the field and in the laboratory to get a better understanding of the behavior of all tested samples.

3. Results and Discussions

Conductance and resistance of the junction reinforced concrete corner

In many structures, continuity between two adjacent ribs is necessary even if these two ribs meet at an angle and a joint in a portal frame is the best example of this.

The internal forces generated in such a joint may cause failure inside the joint before the shaft or threshold, whichever is weaker, reaches the bearing strength.

The corner joint of the portal frame may occur in a two-way frame. The corner joint can be named as follows:

1) Two moment joint.

2) A four-member joint.

3) Three member joint.

Typical examples of these types are shown in Figure 4 in a two-sided joint, the beam torque is completely transmitted to the shaft under it. In a three-sided joint, the beam torque is distributed over the two shafts according to ratios that depend on relative stiffness.

The second type of joint is a link with four sides, in which no torque transmission may occur from thresholds to columns.

Compression reinforcement

The effect of the compression ratio of rebar on the behavior and resistance of the angle joint was mentioned in source [1] ,In this source three tests were compared with each other, where the joints for these tests each contained 1% tensile reinforcing steel.

Reinforcement bar size

What was mentioned in previous studies about the effect of the size of tensile rebar on the behavior and resistance of the concrete joint is small compared to the effect of other variables mentioned [10] He was mentioned that the diameter of the tensile rebar is directly on the behavior and resistance of the joint. Figure 4 shows shape of concrete corner joint.

The reinforced corner joint subjected to loads that lead to closing the angle fails by one of the following types:

1) Flexural failure Figure 5.

2) Bearing failure Figure 6.

3) Shear failure Figure 7.

The effect of these variables can be summarized as follows:

a- The shear strength is inversely proportional to the length of the space.

b- Shear failure load increases with increasing FC'.

c-The shear strength increases slightly when the proportion of reinforcing steel increases, and this effect can be observed especially in the joints containing a low proportion of reinforcing steel [11].

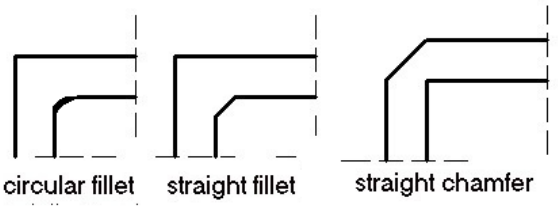

Figure 4. Types of the concrete corner joint cutting

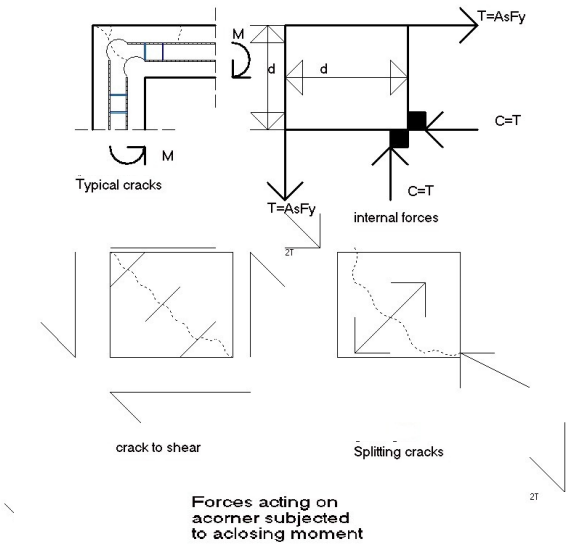

Figure 5. Force acting on the torque-locking joint

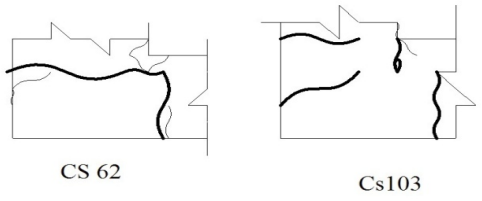

Figure 6. Typical examples of flexural failure [12]

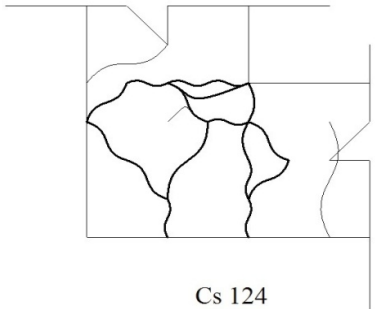

Figure 7. Typical example of loading failure

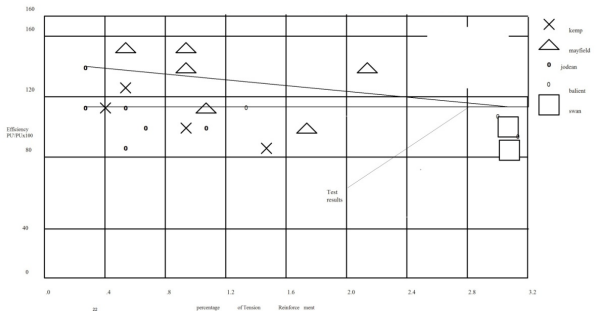

Figure 8. Relationship between efficiency and Percentage of tension reinforcement

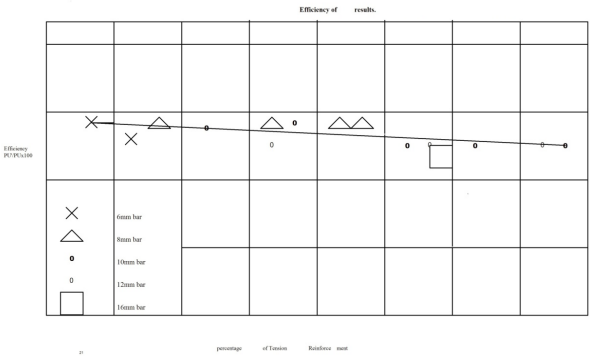

Figure 9. Efficiency of concrete corner joints used

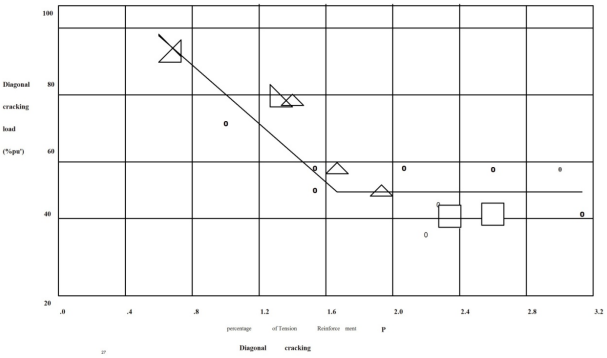

Figure 10. Diagonal cracks

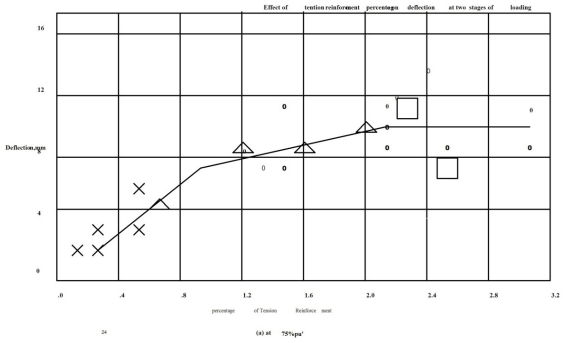

Figure 11. The effect of the tensile reinforced steel percentage on the two loading stages

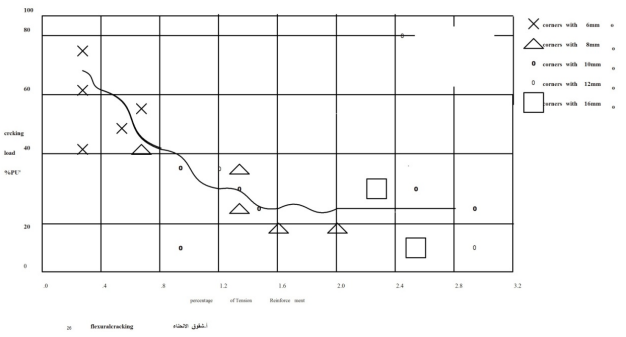

Figure 12. Effect of crack strength on corner joint

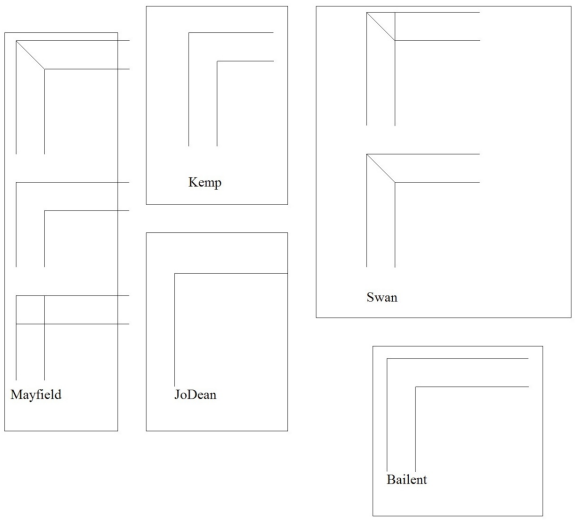

Figure 13. Details of reinforced steel according to researchers references [12-16]

4. Conclusions

Our study is considered the beginning of developing a model to determine the strength and behavior of joints of outer beam columns for earthquake resistance. It also

achieves the balance, compatibility and stress properties of cracked reinforced concrete. This study can provide valuable insights. In the seismic behavior of outer column joints; it is ready to serve analytical purposes such as seismic evaluation of existing joints. This study may result in further development of the angle joints and joints in future work, and the design methods may include this approach well on the same context and format.

References

[1] Richart, F. E., Olson, T. A., & Dolan, T. J. (1938). Tests of reinforced concrete knee frames and bakelite models. *Univ. Illinois Expt. Sta. Bull*, *307*.5.)kemp , E.L. and Makherjee P.R.

[2] Moretti, M. L., Tassios, T. P., & Vintzileou, E. (2014). Behavior and Design of Corner Joints under Opening Bending Moment. ACI Structural Journal, 111(1).

[3] Pham, A. T., Pham, X. D., & Tan, K. H. (2019). Slab corner effect on torsional behaviour of perimeter beams under missing column scenario. Magazine of Concrete Research, 71(12), 611-623.

[4] Nabil, M., Hamdy, O., & Abobeah, A. (2016). Affecting aspects on the behaviour of frame joints. HBRC journal, 12(2), 147-162.

[5] Johansson, M. (1996). New reinforcement detailing in concrete frame corners of civil defence shelters: Non-linear finite element analyses and experiments. Chalmers University of Technology.

[6] Abdul-Wahab, H. M., & Ali, W. M. (1989). Strength and behavior of reinforced concrete obtuse corners under opening bending moments. Structural Journal, 86(6), 679-685.

[7] Sleiman, N. (2017). Tests on GFRP reinforced concrete knee-joints subjected to negative moments (Doctoral dissertation, University of Waterloo).

[8] Moehle, J. P., Hooper, J. D., & Lubke, C. D. (2008). Seismic design of reinforced concrete special moment frames. US Department of Commerce.

[9] ACI Committee. (2008). Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.

[10] Petroski, H. (2012). To forgive design. Harvard University Press.

[11] Al-Khafaji, J. M. N. (1980). The effect of size and percentage of tension reinforcement on the behaviour of reinforced concrete (Doctoral dissertation, University of Southampton).

[12] Swann, R. A. (1969). Flexural strength of corners of reinforced concrete portal frames.2.)Mayfield , B,Kong,F.K Bennison A. and ,davis ,J.C.D.T.

[13] Kemp, E. L., & Mukherjee, P. R. (1968). Inelastic behavior of concrete knee-joints''. The Consulting Engineer, 44-48.

[14] Mayfield, B., Kong, F. K., Bennison, A., & Davies, J. C. T. (1971, May). Corner joint details in structural lightweight concrete. In Journal Proceedings (Vol. 68, No. 5, pp. 366-372).

[15] Mukherjee, P. R., & Coull, A. (1972). Free vibrations of coupled shear walls. Earthquake Engineering & Structural Dynamics, 1(4), 377-386.

[16] Park, S., & Mosalam, K. M. (2012). Experimental and analytical studies on reinforced concrete buildings with seismically vulnerable beam-column joints. Pacific Earthquake Engineering Research Center.

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ARTICLE

Mastering the Production of Electric Vehicles as One of the Modern Instruments for the Development of the Iranian Automotive Industry

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Industry development

ABSTRACT

The article analyzes the problems of introducing electric vehicles, as well as their difference from cars with internal combustion engines. This type of transport has long been included in our everyday life. Today, in the era of the heyday of technology, a person understands that cars with an internal combustion engine (ICE) are almost on the edge of their existence. At present, the development of the production of electric vehicles should be considered as a promising direction of the Iranian automobile industry. At the moment, this market in Iran is not yet occupied by foreign companies, and therefore national companies have a chance to use the strategy of "growth together with the market".

1. Introduction

Despite the constant increase in the reserves of "black gold", in the long term, the oil market will exhaust its possibilities. According to various estimates, with the current and historical production volumes and estimated oil reserves, the oil production volumes of Iran (the sixth world exporters, and the 4th in terms of oil reserves) since 1960 have increased from 1.08 million barrels per day to 3.8 million per day in 2017 year. According to OPEC [24] statistics, the forecast of production and volumes of proven oil reserves is estimated at 157,200 billion barrels. According to the forecast of The World bank, provided that such dynamics persist in the coming years, the country will be provided with a resource for about 155 years. However, in connection with this prospect, the question arises about the transition to renewable energy sources. The impetus for this trend can also be called environmental problems. Thus, according to the World Health Organization, [7] unfavorable environmental factors cause the emergence of more than 100 of the most

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dangerous diseases in the world, which kill 12.6 million people annually. Moreover, about 25% of carbon dioxide emissions into the Earth's atmosphere are produced as a result of the work of various types of transport. According to the IEA, by 2050 [2] this number will double and will continue to grow as the number of private cars increases in developing countries.

2. Methodology

The article examines the features of the development of road transport in the category of the so-called "green" transport. In this work, the authors provide a brief historical analysis of the development of vehicles with alternative energy sources, and also consider the advantages and disadvantages of using such technologies in the field of road transport. The importance of transport for humanity can hardly be overestimated. From time immemorial, he played an important role, constantly developing and improving. The scientific and technological revolution that took place in the 20th century, population growth, urbanization and many other factors brought its development to a completely new level. However, at the same time, a problem arose: a huge number of vehicles caused the deterioration of the ecological situation on a global scale. That is why more and more attention is being paid today to the development of ecological modes of transport. These requirements are associated with the introduction of toughening standards for carbon modes of transport, namely the Euro environmental standards, which regulate the content of harmful substances in the exhaust gases of cars and special equipment, which were introduced by the UN Economic Commission for Europe. In the global automotive industry, in the last decade, there has been a pronounced trend in the development of innovative vehicles based on electric traction. The prevailing production volumes are still for cars based on the internal combustion engine (ICE). However, given the global trends in the fight against environmental pollution, the rapid growth in the number of cars in the world, the development of new technologies and other factors, car manufacturers are actively working towards finding alternative energy sources for use in vehicles. One of the most promising areas is electric vehicles - electric vehicles.

An electric car is a car driven by one or more electric motors powered by batteries or fuel cells. Electric cars have proven to be the best alternative to internal combustion engines to meet the goals of the Paris Agreement. Already, in the course of their life cycle in Europe, 66-69% less greenhouse gas emissions are generated in comparison with gasoline cars, and in 10 years these emissions will be even lower due to the general decarbonization of electricity. Burning carbon-based fuels in the transport sector produces 12 billion tonnes of CO_2-equivalent annually, which is a quarter of the total anthropogenic greenhouse gas emissions. Without widespread restrictions on the operation of vehicles powered by internal combustion engines (ICEs), transport emissions could almost double by 2050 to 21 billion

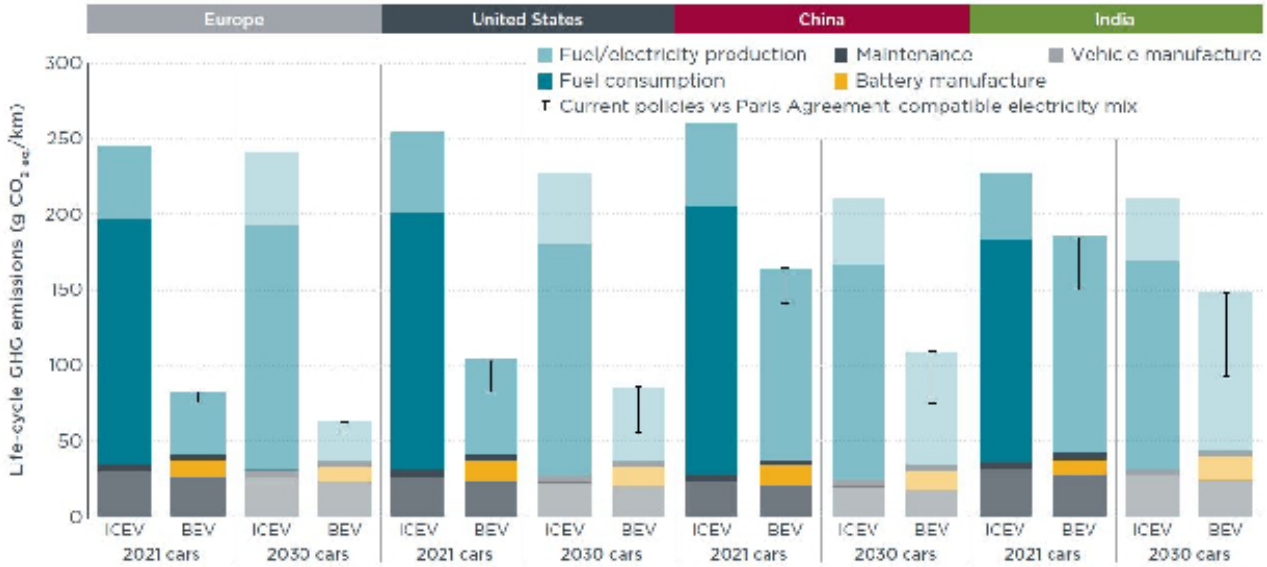


Figure 1. Comparison of greenhouse gas emissions over the full life cycle of internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) in different regions at the moment (2021) and forecast of such a comparison for 2030.

Source: compiled by [25]

tonnes of CO_2-equivalent. To achieve the goals of the Paris Agreement, [25] which involve limiting the increase in the average temperature of the planet to 1.5 degrees Celsius, it is necessary to reduce transport emissions by 80 percent compared to current ones and limit them to no more than 2.6 billion tons of CO_2-equivalent per year.

The massive shift from ICE cars to electric cars and hybrid or hydrogen cars is considered a key tool for reducing greenhouse gas emissions from transport, but the environmental friendliness of such vehicles is still disputed. They may not emit greenhouse gases while driving, but their life cycle leaves a carbon footprint, at least through the production and disposal of batteries. The International Clean Transport Council has published a document comparing the greenhouse gas emissions from vehicles with different engine types and fuels used throughout the life cycle. The calculations took into account the full life cycles of ICE vehicles, hybrid and hydrogen vehicles, and electric vehicles. The study covered Europe (EU countries and the UK), the USA, China and India (full description in Figure 1).

It turned out that even now, over their entire life cycle, compared to gasoline cars, electric vehicles produce 66-69 percent less greenhouse gas emissions in Europe, 60-68 percent in the USA, 37-45 percent in China and 19-34 percent in India, with potential for further reductions. By 2030, significant decarbonization of electricity is expected due to a partial transition to renewable sources, and emissions from electric vehicles in the regions under consideration will be lower by 74-77, 62-76, 48-64 and 30-56 percent, respectively. Hydrogen cars are currently not as clean an alternative to gasoline vehicles as electric ones. Their emissions in the studied regions are lower by an average of 26-40 percent. This is due to the fact that while the market is dominated by "gray" hydrogen, that is, obtained from natural gas. The situation could be changed by the transition to "green" hydrogen, obtained with the help of renewable energy from cleaner sources - for example, sea water. Then the emissions of hydrogen cars will be lower by 76-80 percent. The author of the study stressed that he sees no prospects for hybrid vehicles. Their emissions are, on average, 20 percent lower than those of ICE vehicles, and switching to such vehicles will not be enough to meet the Paris Agreement targets. Modern electric cars are becoming more environmentally friendly and user-friendly: Electric cars have proven to be more environmentally friendly than traditional cars in terms of their life cycle.

The topic of electric vehicles remains one of the most relevant in the field of motor transport within the framework of programs to improve the ecological situation in megacities. Research and development projects are yielding results, and constantly appearing prototypes of equipment allow us to develop and improve the technology of using storage batteries in transport as an alternative to an internal combustion engine. Today, electric vehicles are gradually transforming from the technology of the future into a familiar and popular form of transport, gaining popularity in the automotive market. And it's likely that electric cars will soon replace combustion-powered cars. If we compare the power plants of a traditional car and an electric car, then the advantages of the latter are obvious.

Electric car - cars of the future

As world practice shows, in the context of the growing threat of environmental catastrophe and the limit of oil reserves, innovative trends in the transport industry are aimed at the development of electric vehicles. This is due to the undoubted advantages of these machines. Ecologically clean and resource-saving characteristics, which served as a prerequisite for the development of the market for environmentally friendly modes of transport. To meet more and more stringent requirements, the search for alternative types of fuels for cars - natural gas, biofuels, etc. is being carried out. Emissions from combustion of various types of fuel are shown in Table 1.

In order to get rid of emissions of harmful substances into the atmosphere, you can use electric traction, replacing the internal combustion engine. The advantages of electric transport can also be attributed to the low level of noise and vibration, which helps to reduce noise pollution in the city, good controllability. Nevertheless, the large mass of batteries, the impossibility of long-term storage of electrical energy in batteries, as well as rather complex maintenance does not allow electric transport to take a dominant place in the urban vehicle system. In addition, electric vehicles are dangerous due to the threat of injury to a person by electric shock and electrolytic fluids. Nevertheless, since 2011, the world has seen a real boom in electric vehicles, which is confirmed by the constant growth of sales. Unlike other alternative vehicles, electric vehicles have the lowest cost of ownership. In the urban cycle, a small electric car, without sacrificing mobility, uses on average only 3 kW of engine power, which cannot be compared with the costs of operating a car with an internal combustion engine in this way. The figure for comparing the efficiency of energy use in a classic car and in an electric car (Figure 2) shows that an electric car is almost 2 times more efficient in energy consumption for movement.

Currently, one of the trends in the innovative

Table 1. Emissions from fuel combustion

Fuel	Unit of measure	Pollutant emission factors						
		(CO)	(CH)	(NO_2)	(C)	(SO_2)	aldehydes	benzo (a) pyrene
Petrol	t / t	0,44	0,08	0,025	0,0006	0,001	-	0,23 Ч 10-6
Diesel fuel	t / t	0,125	0,055	0,035	0,015	0,0001	-	0,31 Ч 10-6
LPG	t / 1000 m3 m	0,22	0,05	0,025	-	-	-	-
Biodiesel	t / t	0,03	0,0073	0,054	0,0045	0,0001	98 Ч 10-6	0,175 Ч 10-6
Kerosene	t / t	0,092	0,013	-	-	-	-	-

Source: compiled authors by [29]

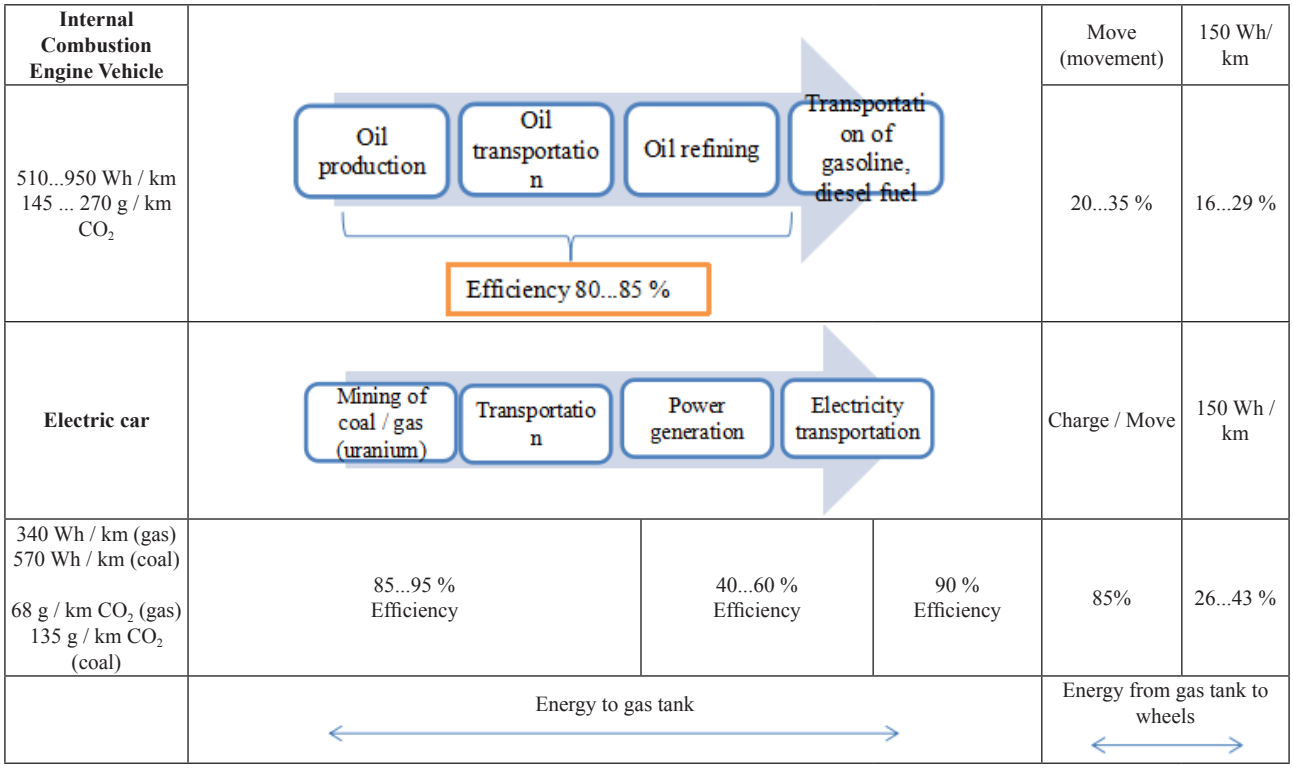


Figure 2. Scheme for comparing energy efficiency in a classic car and in an electric car

Source: compiled authors by [15]

development of the world energy is clean technologies, including those based on the use of renewable energy sources. They already account for more than half of all generating capacities commissioned in the world. Their share in the global energy balance by 2035 [3] should increase from 15% to 23%, and in electricity generation (excluding hydropower) from the current 7% to 20%. Particularly widespread development of promising technologies for the use of renewable energy sources is received in the automotive industry, since due to the growth of the world car fleet (an increase of more than 4-6% per year), the problem of environmental pollution is acute. Electric vehicles are considered a universal solution to the problem of air pollution and reducing the world's dependence on hydrocarbons. The growth rate of the electric vehicle market is impressive: in recent years (2010 - 2020). The market volume has grown 10 times more. According to EV-volumes [8], in 2020 their number worldwide exceeded 10 million. This is only 2.5% of the world park. At the same time, growth is exponential, and

the picture will change quickly enough. There were 3.22 million new electric vehicles registered in 2020, a 68% increase over 2019. What started with an unprecedented economic downturn during the 1st wave of COVID-19 is the success story of EVs in Europe. Almost 1.4 million BEVs and PHEVs were registered in Europe during 2020, up 137% from 2019, in an automotive market that declined 20% year on year. The global share for the full year 2020 is 4% of global auto sales. Full description in Figure 3.

In recent years, the global EV (Electric Vehicle) market share has grown significantly due to energy security concerns, rising oil price trends, and the improvement in the current state of electricity as the cheapest and most efficient energy source for the transport sector in the near future. The global automotive industry is entering a period of profound transformation. A combination of supportive policies and advances in lithium-ion battery technology have enabled electric vehicles to succeed in a market dominated by the internal combustion engine for over a century. Meanwhile, tightening fuel efficiency regulations and urban air quality concerns are increasing pressure on carmakers to improve the rest of their fleet. Electric vehicles (EVs) represent one of the most promising ways to increase energy security and reduce emissions of greenhouse gases and other pollutants. In the long term, electric vehicles are important for Iran as well, if the government seeks to reduce the level of hydrocarbon emissions from ground transportation. Bloomberg New Energy Finance predicts [19] 54% of global car sales will be electric by 2040, with Europe, China and the US being the largest EV markets. Some countries will get there much earlier. In Norway, a leader in EV adoption, sales are already in excess of 40% and the government is aiming to phase out all traditional car sales by 2025. Many global automotive corporations are predicting a "green" future for him.

The prospect of the development of electric vehicles today is beyond doubt. The efficiency of an electric drive reaches 90%, all its energy is mainly used for movement, in cars with internal combustion engines the efficiency is about 25%, and most of the energy goes into heat. In addition, the electric motor does not emit exhaust gases. So far, an electric car is much more expensive than a car with an internal combustion engine. If we take into account the cost of the components of a light electric vehicle, then its payback will be approximately 2 to 3 years. All components for the creation of an electric vehicle are produced in the world, and today the task is: selection, adjustment of the optimal composition and, if necessary, their adaptation to a specific chassis of the car in order to obtain the expected effect. Table 2 shows the main advantages, disadvantages of electric vehicles, as well as barriers to the development of these vehicles.

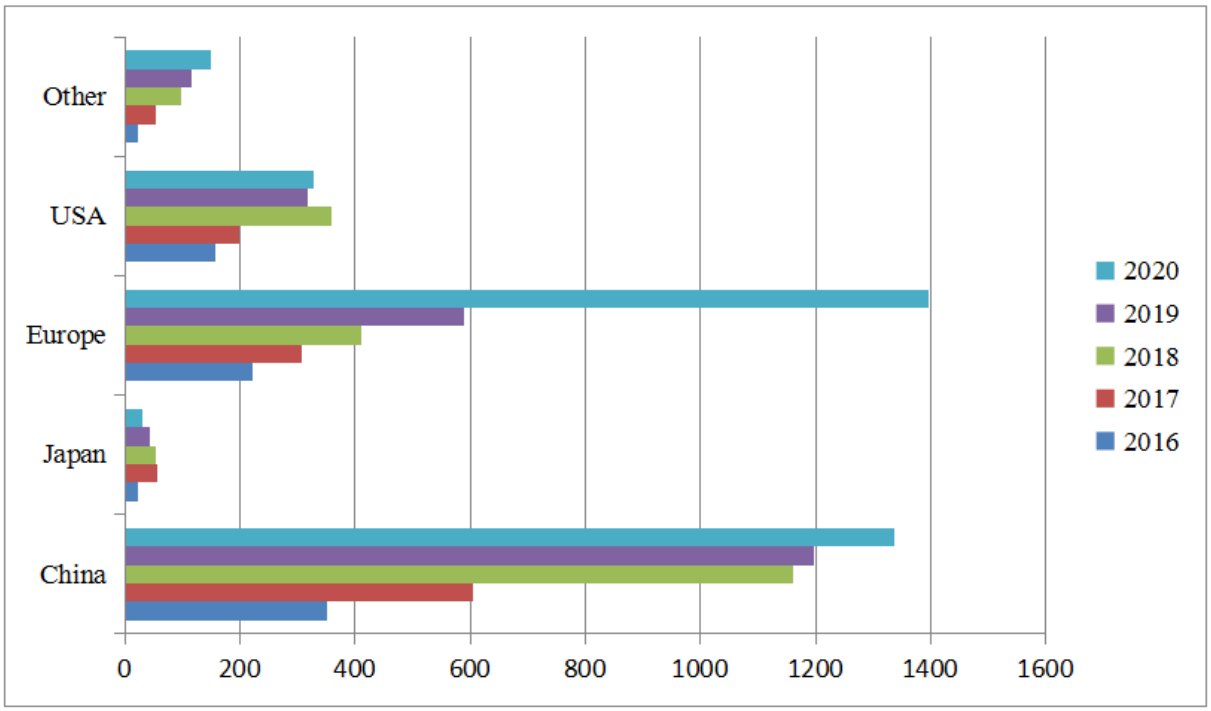


Figure 3. World car sales (BEV - PHEV) and their growth in 2016-2020 (thousand pcs.)

Source: compiled by the author based on [8]

Table 2. Main advantages, disadvantages of electric vehicles and barriers to development

Benefits	Disadvantages
- No environmental pollution, as the electric car does not have an exhaust pipe; - Significantly lower cost of maintenance and ownership; the electric car has very few moving parts, there is no complicated gearbox, the engine control system is much simpler, there is no oil in the engine and gearbox, etc. - Ability to increase the efficiency of using network infrastructure; - State support programs; - Safety. In the event of an accident, special collision sensors will disconnect the batteries, which will cause the car to stop; - Low noise operation of the electric motor; - Ease of controls.	- Lack of developed infrastructure of charging stations; - Long charging time; - Relatively low mileage on a single charge (no more than 300-400 km); - The high cost of an electric car (The price of a car varies from 40,000 to 100,000 €); - Inability to reanimate a fully discharged battery; - A narrow temperature range from 25 to 45 degrees (at 55-60 degrees, the batteries begin to break down, they have to be cooled even when parked in the sun); - The need to replace the battery every 5-10 years (replacement costs about € 15,000); - Disposal of used batteries; They contain environmentally hazardous elements and toxic electrolytes. These elements are subject to regeneration.
Barriers	
Technological issues:	- Technology of immature batteries; - Long charging time; - Influence on the battery from weather conditions.
Social factors:	- The consequences of innovation, which means the changes that innovations make to the current practice of society; - Lack of public charging locations.
Economic problems:	- Selling price
Political factors:	- The provision of financial incentives and consumer subsidies; - Strict regulation and aggressive legislation; - Oil and gas companies were against EV.

Source: compiled by the author

The advantages of electric vehicles:

● Reduced fuel costs. The cost of gasoline is constantly growing and is often consumed in large quantities, which devastates the family budget, and the consumption the electricity bill for recharging the battery should be much less than these costs. ● Reducing environmental pollution. A running electric car engine does not emit harmful gases into the environment. Ideally, to reduce the impact on the environment, it should be produced from clean, renewable energy sources. ● Reduced noise. Electric vehicles are capable of quiet and smooth acceleration, with faster acceleration. ● Security. Electric vehicles go through the same testing procedures as conventional vehicles. Thus, in the event of a collision, the airbags will deploy, the crash sensors will disconnect the batteries, so that the electric vehicle will stop. For example, a Tesla electric car The 2013 Model S received the highest safety rating of any vehicle ever tested in the United States. ● Cost. Gone are the days when electric cars cost a lot of money. Batteries used to be very expensive, but when they are mass-produced, their cost decreases. ● Reliability. Due to the fewer parts and assemblies, the reliability of the electric vehicle increases and, as a result, the cost of repair and maintenance is reduced.

Disadvantages of electric vehicles:

● Stations for recharging. So far, the infrastructure is in its infancy. ● Electricity is not free. It is worth paying attention to the fact that electric vehicles have different energy consumption. ● Short mileage and limited speed. Most EVs can travel anywhere from 160 to 240 km on a single charge. Although some models promise to travel up to 480 km without recharging. ● Recharge time. For a full charge an electric car takes about 8-10 hours. ● They are usually 2-seater. Electric cars are not designed to transport the whole family, which means that the trip for three may already be inconvenient. ● Battery replacement. Replacement is in progress every 3-10 years. ● In winter, the battery consumption increases for heating the passenger compartment, brushes and headlights. This leads to the fact that the mileage in winter is reduced by 30-50% compared to the summer period.

Even despite the fact that there are many nuances in the use of electric vehicles, one should believe that they will be resolved in the future. First of all, you need to think about the fact that the main advantage of an electric car is reduction of the degree of environmental pollution. The demand for electric vehicles can change significantly in the following cases. Firstly, with a 10-fold increase in gasoline prices in the country, that is, a worsening situation with exhaustible energy resources (oil and gas reserves). Secondly, the price reduction for electric vehicles, which will be possible as a result of a technological breakthrough.

Table 3. Comparative characteristics of consumer properties of cars

Technology	Passenger car	Electric vehicle
Distance traveled per unit of fuel	18 km/L	110 W * h / km
Charging time, h	0,2	4-8
(CO_2 emissions) g / km	39,0	12,1
Energy efficiency, km / MJ	0,63	2,18
Noise	+	-
Cost of 1 km, €	0,12	0,008
Service cost per 1 km, €	14	6

Source: compiled authors

It is worth noting that when using an electric car,

the owner gets significantly more privileges. States are striving to bring as many green electric vehicles onto the road as possible by offering instead of exemption from a certain list of taxes, free parking spaces, free charging vehicle, the ability to drive on the line public transport, which reduces the likelihood of getting traffic jams to a minimum, and, of course, profitable interest-free loans for the purchase of an electric car. Nowadays, governments around the world are embracing the development of EV on the road, setting goals to improve this industry. Here it would be appropriate to recall the experience of Ford, who "buried" the entire carriage industry more than a hundred years ago. The experience of Apple, which managed to significantly reduce the personal computer (PC) market by squeezing a PC into a phone, and in a few years became not only the flagship in its industry, but also the largest company in the world, overtaking such giants as General Electric and Exxon Mobil, which recruited its power for over a hundred years. In 2015, Germany announced a complete phase-out of ICE vehicles by 2050. Later, in March 2016, the Norwegian authorities officially announced a complete abandonment of sales of cars on gasoline and diesel fuel in the country by 2025, planning for this goal about 1 billion euros of investments. In general, the authorities of almost 40 countries reacted positively to the introduction of electric vehicles.

Trend, problems and prospects for the development of an electric car in Iran

In recent years, there has been a significant increase in the car park in Iran. The country's motorization rate is not very good even in Asia, with 220 cars per 1000 inhabitants. In total, 19.5 million vehicles are registered in the personal property of citizens [20]. The volume of passenger transportation by road and the share of road transport in the total volume of cargo also increased. Thus, according to the estimates of the Center for the Study of Transport and Traffic Jams [19] in the roads of the city of Tehran with 4 million vehicles, about 17.5 million trips are carried out every day (an increase in the share of trips from 39% in 2011 to 45%). Table 2 shows a general picture of a number of factors from which Iran's motorization can be expected to increase in the coming years.

Table 4. Overview of the automotive market of Iran

		2006		2020		2030	
Population (million People)	Urban	48.2	70.4	57.8	79.4	72.6	95.5
	Rural	22.2		21.6		22.9	
Ground Trips (Millions of Trips)	Bus	121		140		177.4	
	Personal car	313		410		586	
Family of existing car (million people)		28		42.1		64.6	

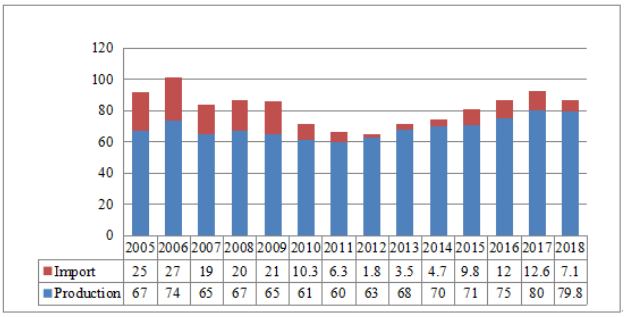
Source: compiled by the author according to [5]

The data in the table show that the population of the country is growing during the period under review, the more the growth rate of the urban population is much higher than the rural population. Thus, the urban population (from which one can expect more car purchases than the rural population), amounting to about 49 million people in 2006, grew to 58 million in 2020, and is projected to grow to 73 million in 2030, and, accordingly, the total population to the level of 96 million people. Also, following the data on the number of ground trips, we notice that their growth rates are from 20 to 25%. However, the share of trips by private cars is more than 72%, 74% and 79%. According to the researchers [1], due to factors such as cheap fuel, and the development of roads in the country, more than 90% of the transportation of passengers and goods by roads is carried out (Although it should be borne in mind that the shortcomings of Iran's railway and air lines the development of vehicles). As of 2020, the length of the public road network in Iran is [21] 85.6 thousand km, and is expected to increase in the coming years.

According to the Department of Planning and Transport Economics in 2006, only 6% of Iran's passenger traffic was carried out in trains and airplanes, and the rest was carried out using land transport. Considering another indicator (the family of an existing car), the growth of the indicator is immediately noticeable from 28 million people in 2006 to 42.1 million in 2020, and to 64.5 million in 2030. Understanding the fact that the above indicators will affect the increase in the level of motorization in Iran, it is quite possible to expect an increase in the number of cars in the coming years. In addition, it is worth noting that about 1.350 million old cars are driven in the country, and their number is growing annually by about 200 thousand cars, according to “Talai M.”, a representative of the country's recycling centers for old cars [6]. Since the average age of passenger cars in the country is more than 10.5 years, and according to various estimates, 26% of the total vehicle fleet in Iran is more than 20 years old. However, the growth of Iran's car fleet leads to the fact that, firstly, emissions and air pollution increase, and secondly, gasoline consumption is growing. Moreover, the cars produced by Iranian automakers do not comply with environmental standards. Below we will consider the consumption of gasoline from 2005-2018 to Iran.

Considering the data in Figure 4 understands the fact that as a result of the massive use of non-environmentally friendly road transport in the cities of Iran (including old and new), more than 90 million liters of gasoline are consumed daily in the country. As a rule, non-rational consumption of gasoline and energy losses for long-

term periods will not be beneficial for the people and the country as a whole. Although the culture of consumption of the population, and the management problems of the government in real life can be considered one of the reasons for the problems. The government sometimes proceeds from the assumption that a solution to the problems can be found through an increase in the price of gasoline, but the research carried out by "Sadeghi H." [26] from the University of Lorestan showed that the price of gasoline strongly influences the inflation rate of a country. So in a study using ARDL models from 1978-2013, the results show that a 1% increase in the price of gasoline - 1.112% increases the country's inflation rate. This is 0.748% for diesel fuel. Since the increase in the price of gasoline, not only does not reduce the consumption of gasoline, but also creates problems with the growth of inflation.



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Import	25	27	19	20	21	10.3	6.3	1.8	3.5	4.7	9.8	12	12.6	7.1
Production	67	74	65	67	65	61	60	63	68	70	71	75	80	79.8

Figure 4. Gasoline consumption by Iranian vehicles (share of imports and production) - million. Liters / day from 2005-218

Source: compiled by the author based on [22,23,31]

Table 5. compares the gasoline consumption of the neighboring country Turkey with Iran.

Turkey		**Iran**
79 million	Population	80 million
21 млн. 80 million	Vehicle	19 million
8 million	Gasoline consumption liter / day (average)	85 million
3 billion	Gasoline consumption liter / year	30 billion
1.5 $	Gasoline price	0.18 $

Source: compiled by the author based on [34,13,35]

The data in the table show that Turkey, having a larger vehicle, consumes 10 times less gasoline than Iran and, accordingly, spends 10 times less money, and clearly much less subsidies for gasoline. Thus, with an average consumption of 30 billion liters of gasoline per year, and with an average world gasoline price of 1.15 $ [13], Iran spends about 34.5 billion $. If the compensated amount is deducted from this amount with the help of gasoline consumers (paying 0.18 $ when buying gasoline per liter), then it is understood that the state pays subsidies in the amount of more than 29.1$ billion annually. Confirmation of this can be considered the words of Iranian Oil Minister "Zangane M." [30], according to which the annual subsidies for fuel and energy are estimated at 40 billion dollars, which in turn is considered a threat to the country, but solving problems can turn this threat into an opportunity. It should be noted that a large share of these subsidies, as we said earlier, is the share of gasoline subsidies. It should be noted that a large share of these subsidies, as we said earlier, is the share of gasoline subsidies. Thus, the consumption of gasoline in Iran reduces the country's budget in the amount of 29.1 billion $, and besides the fact that the state needs to compensate such an amount annually, we must not forget about the creation of environmental problems with the consumption of such a volume of gasoline.

Although, as we said earlier, the new Iranian cars do not comply with international environmental standards, but the majority of Iran's car parks are more than 10-15 years old, which in turn leads to an addiction to the consumption of gasoline, and consequently to air pollution. So in the study of the organization of energy productivity in Iran in 2011, [10] it is shown that the consumption of 60 million liters of gasoline per day creates 138 thousand tons of carbon dioxide. On this basis, the level of generated carbon dioxide is currently growing to 186 thousand tons per day, because gasoline consumption rose to 81 million liters per day. Urban air pollution is a serious health risk in several major Iranian cities. The main drivers of transport, as stated, are the widespread use of fossil fuels, outdated urban fleets of gasoline and diesel vehicles, industrial sources within and near city boundaries, and natural dust. For decades, most of Iran's major cities have faced severe air pollution problems. The problem first became apparent in Tehran, followed by other cities including Mashhad, Arak, Isfahan, Ahvaz and Tabriz. According to the World Health Organization, [28] cities in three countries, Iran, India and Pakistan, are among the most polluted cities in the world. Today, urban air pollution poses an immediate health risk to a large sector of Iran's population. According to the head of the fresh air department of the Iranian Ministry of Health "Shahsovani A.", [17] 33,500 people die in the country every year due to environmental problems. So the average concentration of suspended particles in 2015 in 25 cities of Iran was estimated at 31.7 mg. per cubic meter, although in comparison with 2011 it had a decrease from 39 mg. Also a member of the Tehran City Council "Farahani M." [16] compares the environmental

deaths in Tehran to the crash of an airbus that seats 500 people every week.

Tehran, home to over 8.5 million people, has suffered from high concentrations of carbon monoxide in the past, but has recently suffered from high levels of particles. The contribution of various sources to Tehran's air pollutant emissions is calculated as follows: vehicle 75-80%, industry 10-15%, domestic and commercial 5-10%. Also, Mashhad, Isfahan and Tabriz face similar problems, while Arak's air pollution is mainly due to industrial sources. The variety of sources of air pollution in Iran makes it more challenging. Among the ten causes of death in Iran, four are associated with arthrosclerosis with air pollution among its main risk factors. Some air pollutants also irritate the lungs and respiratory system. Short-term effects include discomfort, allergic reactions, coughing, and sneezing. Long-term exposure to certain pollutants can also cause lung cancer. Air pollution is especially harmful to sensitive groups such as small children, pregnant women, and the elderly. Air pollution can also damage historic buildings and structures over time through corrosion. The most hazardous air pollutants are fossil fuel products, primarily a byproduct of combustible fuel engines in most cars. Although their concentrations are regulated in most major cities, they still pose a risk to human health.

The first air quality monitoring station (AQM) [14] in Iran was established in 1992 by the Department of the Environment (Sazeman-e Hefazat-e Mohit-e Zist). Since then, around 200 AQMs have been established around Iran. In the capital alone, thirty-nine AQMs are operated by the Department of the Environment in partnership with Tehran Air Quality Control Company (AQCC), a subsidiary of Tehran Municipality. A study by researchers from the Faculty of Medicine of the University of S. Beheshti [18] showed a close relationship between various air pollutants and the number of cases of severe acute respiratory syndrome. The relationship between air pollution and acute respiratory symptoms in patients admitted to Tehran's emergency centers in 2013 was assessed. 36,787 patients with acute respiratory symptoms were enrolled in these centers. Data were collected on the number of cases with acute respiratory symptoms and air pollutants at air quality monitoring centers. Moreover, Poisson regression was used to estimate the relationship between the concentrations of air pollutants (PM2.5, SO_2, NO_2, O_3, CO) and the number of cases of severe acute respiratory syndrome. The results of the study showed that CO (average weekly IRR = 1.1) and SO_2 (average for three days IRR = 1.03 and average weekly IRR = 1.04) increased the risk of respiratory diseases by 10%, 3% and 4%, respectively. Consequently, a longer duration of contaminants will increase the risk of respiratory syndromes. According to the results of this study, elevated air pollutant concentrations may be associated with an escalation in the number of patients with acute respiratory symptoms related to emergency medical centers in Tehran.

Consequently, a longer duration of contaminants will increase the risk of respiratory syndromes. According to the results of this study, elevated air pollutant concentrations may be associated with an escalation in the number of patients with acute respiratory symptoms related to emergency medical centers in Tehran.

Annual estimates of air pollution in Iran [12] show that the damage caused by air pollution in Iranian cities is 640 million $ annually. Thus, according to the World Bank, the damage from the disease caused by air pollution is estimated annually at 260 million $ for the Iranian economy. According to the studies carried out, all domestic vehicles have a higher fuel consumption, and at the same time do not comply with environmental standards.

It should be noted that cars not only pollute the air with toxic gases [36], they also burn oxygen. To burn one kilogram of gasoline, 13.7 kg of air is required, that is, 2.9 kg of oxygen. Already, the planet burns about 90% of all oxygen produced by terrestrial vegetation. Thus, the largest air pollutant in Iran is road transport. Given the difficult environmental situation in Iran, the government will need to introduce stricter requirements at the regulatory level regarding the environmental friendliness and energy efficiency of vehicles.

From the data given in the table, it can be seen that Iranian cars, consuming high fuel consumption, emit more emissions and pollution than similar ones in international production. Thus, the largest air pollutant in Iran is road transport. Given the difficult environmental situation in Iran, the government will need to introduce stricter requirements at the regulatory level regarding the environmental friendliness and energy efficiency of vehicles. Analysis of the situation in Iran shows that most of the light vehicles, which account for the main emissions of harmful substances, are in private use and are concentrated in large cities. Passenger cars are mainly used as personal transport for movement in urban conditions, while the average mileage per day does not exceed 100 km. Thus, the gradual replacement of personal vehicles in large cities with electric vehicles is quite realistic and expedient from an environmental and economic point of view.

The development of electric vehicles is a promising area in the activities of automakers. But the outlook for the

Table 6. Pollution and average fuel consumption of the Iranian fleet

Emission standard	Engine volume (cu. Cm)	Manufacturer	Emission factors (g.km)				FC (liter/100 km)
				CO	HC		
E2	< 1500	Iranian	163.66±10.77	4.16±1.26	0.42±0.12	1.3±0.42	8.98±1.02
	1500-2000	Iranian	233.2±14.92	11.22±3.76	0.70±0.34	1.61±0.35	11.68±0.88
Norms E2				2.2	0.5	0.5	
E4	1500-2000	Iranian	146.91±25.22	1.12±1.15	0.04±0.02	0.04±0.02	6.69±1.48
		Imported	163.55±15.55	0.35±0.36	0.04±0.03	0.02±0.02	7.01±0.67
	>2000	Imported	207.84±17.64	0.80±0.67	0.04±0.02	0.05±0.04	8.91±0.85
Norms E4			155	1	0.10	0.08	
Mini truck			245.70±40.34	8.68±1.18	0.51±0.33	1.47±0.99	11.34±1.61

Source: compiled by the author according to [30]

development of electric vehicles is fraught with a number of challenges. These problems depend both on technical progress in the field of energy-saving technologies in road transport and on the geopolitical situation in the country. Their use will significantly reduce oil consumption, increase transportation efficiency, reduce fuel costs, as well as minimize the amount of toxic substances emitted into the atmosphere during the operation of vehicles. One of the significant reasons for the lack of attractiveness of the electric vehicle for the majority of Iranian consumers is its high price. For example, the average cost of an electric car on the Russian market ranges from 12,000 $ (Mitsubishi i-MiEV) up to 70 thousand $. (Tesla Model S), and this is a rather high price with an average wage in Iran of 500-600 $. But dropping the price of EVs, especially early-stage tech innovations without huge demand, isn't easy. However, the situation is changing with an increase in production volumes. Gasoline price is another key factor in EV buying decisions, as evidenced by several studies. The general trend is that EV adoption increases as the price of gasoline rises. The persistence of low gasoline prices for political or non-political reasons has negatively impacted the EV adoption rate in the past.

The main limiting factor in the growth of the electric vehicle market can also be considered the lack of infrastructure for their operation, primarily a developed network of charging stations. So as the number of EVs increases, the demand for their charge will increase. This increase in load can adversely affect the power system if not properly managed. The Vehicle-to-grid (V2G) system can play an important role in smoothing out the demand load. In its study, 'Sierzchula' [32] believes that adding one charging station per 100,000 inhabitants will increase the EV market share by 0.12%. Also in his opinion, the addition of one separate charging station could have a double impact on EV market share than a 1,000$ increase in financial incentives. To overcome the barrier to charging infrastructures, it is necessary to invest in easily accessible charging stations.

According to various data from EVI (Electronic Vehicles Initiative), the deployment of mass consumption of electric vehicles is taking place in the United States, Norway, Germany, Japan and others. In most cases, the government pays attention to supporting both supply and demand. Financial incentives for consumers at national and local levels are well thought out. Such events give confidence to automakers and consumers in the further development of the market. The mix of non-financial incentives is also paying off. The electric vehicle market in Iran is currently still in its infancy. The number of owners of this type of transport is not subject to counting, and official statistics are not presented. The reluctance of Iranian consumers to buy a "green car" is primarily due to the low level of effective demand, the lack of a network of electric charging stations, the lack of incentive policies (subsidies, tax incentives) and public awareness of the benefits of electric vehicles. Also problems with road infrastructure, lack of a service station. The electric vehicle market in Iran will face a wide range of challenges that require active government support. However, the implementation of an effective policy will lead to an increase in the welfare of society, an improvement in environmental performance, and contributes to the energy security of the state. The ongoing research and development work of domestic companies in this area are, in our opinion, the main lever capable of solving this innovative problem.

The relatively low cost of electric energy and low maintenance costs of an electric vehicle are indisputable advantages over vehicles using an internal combustion engine as a power plant. The energy used in electric vehicles is many times cheaper than gasoline. In Iran, electricity is several times cheaper than in other countries, therefore, electric vehicles on the market should be of great interest in order to save money. Thus, according to the report of Bargh News [4], the nominal capacity of electricity production in the country was declared 75 thousand 365 MW, which gives Iran a significant

opportunity to lead in the field of electricity in the region. Since assuming the low price of electricity and the ability to generate consumed electricity, the transition from gasoline to electric vehicles is quite expedient.

Table 7. compares electric vehicles with 2 popular Iranian and world gasoline vehicles.

Indicator	Tesla Model S	MB-S Class	Samand Soren
Price,$	71 070	115 800	7 700
Consumption per 100 km (in gasoline, equivalent), liter	2	13	11,5
Cruising range, km	450-500	600-800	555
Acceleration to 100 km / h, sec	3	5	14.5
Maximum speed, km / h	700	455	185
Possibility of free refueling / charging	Yes	No	No
Government support	Yes	No	Yes
Infrastructure development	Low	High	High
Security level	High	High	Middle
Noise	-	-	+
The cost of 1 km, €	0,009	0,11	0,1
Cost of service per 1 km, €	6,73	13,41	
Charge time, h	4-8	0,2	0,2
(CO_2 emissions) g / km	12,6	39,0	E-4

Source: compiled by the author

From the table we can see that an electric car is cheaper, although it has significantly better characteristics. The only drawbacks are poorly developed infrastructure, but this problem is already at the stage of solution. However, an electric car is inferior in some characteristics to MB, and in comparison with Iranian cars, it is much better, environmentally friendly, and safe. As a result of the massive use of electric drives in automobiles, by 2050, oil consumption in the world will sharply decrease. This will bring significant losses to the Iranian budget, which is directly dependent on oil prices. As a result, the country will face problems if the economy is not diversified. In this regard, one of the first steps of the government should be to revise the policy in the automotive industry, change the priorities of the country's motorization, and take urgent measures to develop renewable energy, taking into account current trends. This should become one of the priority national projects. Pilot projects for the development of non-polluting renewable energy sources and the use of electric vehicles should be implemented in a blissful future. Only such a decision will make it possible to adequately respond to the challenges of the 21st century in the field of road transport. Otherwise, our automotive industry will remain completely technologically backward, while others will change the entire road transport system to an innovative one.

One of the problems of modern electric vehicles is the relatively low range on a single charge. At the same time, the average charging time for electric vehicle batteries is about 4-8 hours, depending on the battery capacity and the amount of charging current. According to the International Energy Agency, at the beginning of 2020, there were just over 860 thousand connection points at charging stations in the world. And only a third of them have fast charging capabilities. Research shows that vehicles are not used for active transportation more than 90% of the time, so during this time, electric vehicle batteries can be used to serve electricity markets without damage. Navigant Research estimates that global revenue from V2G solutions will grow to $ 190 million by 2020, and the global energy storage market will be $ 80 billion by 2025. Another limiting factor for the mass market entry of electric vehicles is the lack of a viable and cost-effective business model. If you look at the leaders-car manufacturers of electric vehicles, GM, Tesla, Mercedes-¬Benz, then these manufacturers cover the unprofitability of their electric projects with revenues from the sale of traditional cars with internal combustion engines. In 2020, Ford Motor scrapped plans to produce an electric crossover under the Lincoln premium brand, incurring losses of $ 500 million. Earlier, Dyson planned to invest $ 2.7 billion in a new direction and acquired several start-ups in the development of technology for electric vehicles. The company even developed a prototype, but eventually closed the project. “The Dyson team has developed an amazing electric vehicle. But we just don't see how to make it commercially viable, ”said CEO James Dyson. Finally, the complete or partial abandonment of conventional cars with internal combustion engines can provoke a significant increase in the price of electricity and its shortages. According to BloombergNEF research, the ubiquity of electric vehicles will lead to a 6.8% increase in electricity consumption worldwide by 2040, which corresponds to the additional 1,350 TWh required to charge electric vehicles [9].

Additional electricity will also be required to mine the rare earth metals used in batteries. All of the above facts indicate that the state has an important, but not a decisive role in expanding the electric transport market. In the era of the global economy, it is necessary to take into account many factors when developing a strategy for an innovative product to enter the market, which even claims to change the paradigm of urban mobility and solve environmental problems. The development of electromobile transport

is considered today by many countries of the world as a way to solve existing environmental problems, the possibility of forming new markets for innovative products and therefore is actively supported by the state in various ways. At the same time, the main barriers to the development of "green" transport are cost (high price for electric vehicles) and infrastructure (lack of the necessary structure for charging, replacement and disposal of batteries). Experts consider measures of state support of demand for environmentally friendly modes of transport adopted in many European countries, the USA and China, as well as technological advances in the production of batteries, which reduce the cost of the most expensive element of an electric vehicle - a battery, as the main drivers of growth in the global electric vehicle market.

The prospects for the development of electric vehicles in Iran are directly related to the general political direction in this aspect. It is important to note that the production of electric vehicles in Iran should be perceived as a new high-tech industry that is a symbiosis of transport, energy and information technology. Targeted investments in electric vehicles as a new industry create new types of goods / services and, as a result, new jobs, while solving important environmental and social problems. Thus, the development of the electric vehicle market for Iran will become one of the innovative and promising areas that will allow utilizing the existing developments of the domestic industry, creating a new high-tech industry, attracting foreign investments and technologies to the country, and solving several social and environmental problems. However, the development of electric vehicles must take place with the active participation of energy companies in the creation of infrastructure, since this infrastructure and new types of unplanned loads will significantly affect the reliability and quality of power supply.

3. Conclusions

The conclusion suggests itself: lower prices for electric vehicles will promote the popularization of this type of transport in Iran, and create demand for them. For the further development of the electric vehicle market in the country, joint efforts and the adoption of initiatives both at the state level and with the participation of private business are needed. Based on the experience of foreign countries that hold leading positions in the global electric vehicle market, the main attention should be paid to the study of such factors that determine the attractiveness of this segment for consumers, such as: economic (purchase price, charging price, number of potential buyers); political (subsidies, tax incentives, customs duties, non-monetary incentives, etc.); technological (assortment and model range, charging time, technological innovations). The horizon of waiting for a total transition to electric vehicles may turn out to be quite distant, Iran is still at an early stage of their development, so the electric vehicle market has yet to take off, but this must be done, since this is a real world trend, and the only chance to raise the country's auto industry, while the state gets rid of from unnecessary subsidies for gasoline, and the country will have a normal fleet of vehicles with environmentally friendly clean air.

References

[1] Analysis of the automotive industry. Study department and investment research. Pension organization of the country. May 2009. 400 P. [in Persian].

[2] Antonenkov V.O., Cygankov D.V., Lukashov N.I. The development of electric vehicles in the modern world. // New Science: Theoretical and Practical View. 2015. № 4. Pp. 84-86. [in Russian].

[3] Bakhteev SH.R., Bakhteev K.R. Analysis of the state of the electric vehicle market in Russia and its development trends. // In the collection: Generation of the future: View of young scientists. 2017. Pp. 36-41. [in Russian].

[4] Barghnews // What is the strength of Iranian energy? URL: http://barghnews.com/fa/news/16924/ [In Persian].

[5] Comprehensive Transportation Plan of the Country. Office of Planning and Transportation Economics 2016. Pp.325. www.mrud.ir.

[6] Donyae-e-eqtesad Newspaper. // How many old cars are there in the country? URL: https://donya-e-eqtesad.com/ [in Persian].

[7] Ecotechnica. Due to poor ecology, 12.6 million people die every year - a quarter of all deaths in the world. *URL:* https://ecotechnica.com.ua/ekologiya/902-iz-za-plokhoj-ekologii-ezhegodno-umiraet-12-6-mln-chelovek-chetvert-ot-vsekh-smertej-v-mire.html [in Russian].

[8] EV-Volumes. The electric vehicle world sales database. Global Plug-in Vehicle Sales for 2020 - Final Results. URL: http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/

[9] Electric vehicles: global trends, problems and prospects. URL: https://energypolicy.ru/elektromobili-mirovye-trendy-problemy-i-perspektivy/energoperehod/ [in Russian].

[10] Electric vehicles. Division of electricity and fuel production. Energy Productivity Organization of Iran (SABA). Autumn 2010. 23 C. [In Persian].

[11] Euro emissions standards. URL: https://www.theaa.com/driving-advice/fuels-environment/euro-emissions-standards.

[12] Ganavati E., Barzegar S. Assessment of air pollution and its impact on human health. Shahrdariha Journal. 9th year. No. 95. S. 24-28 [In Persian].

[13] Global Petrol Prices // Gasoline prices, liter. URL: https://www.globalpetrolprices.com/gasoline_prices/.

[14] Hosseini V., Shahbazi H. Urban Air Pollution in Iran. Iranian Studies, 2016 Vol. 49, No. 6, 1029-1046, URL: http://dx.doi.org/10.1080/00210862.2016.1241587.

[15] Ivanov S.A., Asadov D.G. Market analysis and development trends of lithium-ion batteries and electric vehicles. International technical and economic journal. Issue: No 1 (2011) Pp: 119-122 [in Russian].

[16] Iranian Students' News Agency. The victims of air pollution in Tehran every week equals an Airbus crash of 500 people. URL: https://www.isna.ir/news/96080703781/ [In Persian].

[17] Mashreghnews. Air pollution how many Iranians are killed every year? URL: https://www.mashreghnews.ir [In Persian].

[18] Motasedi S. Evaluation of the Association between Air Pollutants and Number of Cases with Severe Acute Respiratory Syndrome Recorded at Emergency Medical Centers in Tehran, Iran in 2013. Journal of Health Research in Community. Volume 2, Issue 2, Summer 2016. C.38-44.

[19] McKerracher., Colin. Will electric vehicles dominate the future vehicle mix? Bloomberg New Energy Finance. URL: https://about.bnef.com/blog/will-electric-vehicles-dominate-future-vehicle-mix/ December 6, 2017.

[20] Mehr News Agency (MNA). // The car park in the following years reaches 40 million. URL: https://www.mehrnews.com/news/4085393/ [in Persian].

[21] Official site of the Ministry of Roads and Urban Development. // Summary of roads and road transport in the country. URL: http: //www.rmto.ir. [in Persian].

[22] Official website of the Iranian Ministry of Oil. URL: http://mop.ir [in Persian].

[23] Official site of the National Iranian Oil Company. URL: http://nioc.ir [in Persian].

[24] Organization of the Petroleum Exporting Countries (OPEC). // Iran facts and figures. *URL:* http://www.opec.org/opec_web/en/about_us/163.htm.

[25] Popova M. Electric cars turn out to be more environmentally friendly than traditional cars, taking into account their life cycle. URL: https://nplus1.ru/news/2021/08/04/comparison-of-life-cycle [in Russian].

[26] Sadegi H., Tamari E. Research project on recycling of old cars with game theory approaches. Journal of Economic Modeling. Eighth edition No. 4 "28" P.83-102. [In Persian].

[27] Salarvandian F., Dijst M., Helbich M. Impact of traffic zones on mobility behavior in Tehran, Iran. Journal of Transport and land use 10.1 [2017] pp. 966.

[28] Salakhshurfard H. Air pollution. Shahed University. General health care and advice. 62 P. [In Persian].

[29] Sivakov V.V., Pesenko M.V. Analysis of the electric vehicle market. New materials and technologies in mechanical engineering. 2017. No. 26. Pp. 87-91 [in Russian].

[30] Shana Oil and Energy Information Network. // Iranians consume 5.5 million barrels of fuel per day. URL: https://www.shana.ir/fa/newsagency/281268/ [In Persian].

[31] Shata // Oil and Energy Information Network. URL: www.shana.ir [in Persian].

[32] Shima Hosseinpour, Hongyi Chen, Hua Tang. Barriers to the Wide Adoption of Electric Vehicles: A Literature Review Based Discussion.URL: https://www.researchgate.net/publication/304626623.

[33] Shima Hosseinpour, Ona Egbue. Optimizing the Dynamic Scheduling of Electric Vehicle Charging and Discharging. Proceedings of the 2015 Industrial and Systems Engineering Research Conference S. Cetinkaya and J. K. Ryan, eds. https://www.researchgate.net/publication/280568277.

[34] Tejaratemrouz // Why does Iran consume 10 times more gas than Turkey? URL: http://tejaratemrouz.ir/fa/news/30151/ [In Persian].

[35] The World Bank Group. // Where we work. URL: http://www.worldbank.org/en/where-we-work.

[36] YUTT E., Stroganov V. I. Electric cars and cars with a combined power plant calculation of speed characteristics. Tutorial. Moscow Automobile and Highway State Technical University (MADI). Moscow 2016.109 p. [in Russian].

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ARTICLE

Change in Adaptability of Residential Architecture: Spatial Analysis on Traditional and Contemporary Houses of Bangladesh

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ABSTRACT

This study focused on spatial analysis to identify the changes in adaptability over the last five decades. The features influencing adaptability were selected from the reference study. An appropriate method was used to analyse these features through spatial analysis. Six distinctive typologies of rural houses were selected from six regions. Unlike the traditional houses, the contemporary houses in the same area reflected a different character. Urban houses built since the early and mid-20th century were compared with contemporary houses. After analysing the openness, generality, flexibility, depth, typicality, construction technique, involvement of end-users, and the feedback from the inhabitants, the study identified a significant decrease in contemporary houses' adaptability. Spatial analysis was used to quantify the different features and comparison between traditional and contemporary houses. Though the adaptability had been reduced over time, the latest houses started to achieve better flexibility in some features due to government policy and implementation of statutory building regulations. Further recommendations were provided to enhance the residential architecture's adaptability in future. The study samples were selected from different regions of Bangladesh. Still, the result and policy recommendations can be helpful for other countries, especially with high population density and a developing economy.

1. Introduction

Adaptive architecture can respond to the changing environment, the needs of the inhabitants, and function. Though any building can be modified according to the changing need, the ease of the process and user interaction are essential. Transformable surfaces, modular design, spatial features, and building technology can enhance adaptability [1]. Socio-cultural impact and economic condition can influence the acceptance of adaptive architecture to the end-user. Since the initial cost is comparatively higher for adaptable buildings, it is essential to evaluate the long-run benefits of making it feasible for developing countries. An adaptable building's life cycle is significantly longer than the standard residential developments, making it economical in the long term [2,3]. Moreover, the multifunctional use of spaces, spatial optimisation, and coping with dynamic conditions

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will benefit the high-density cities of developing countries [4]. Several experimental designs on adaptable architecture reveal that the same space can accommodate different users [2,5]. In a study conducted by Architect Le Corbusier, a different setup of the same space has been proposed for daytime and nighttime use to accommodate the temporal change in need. The homogenous character of different rooms can enhance adaptability, as we can see in Traditional Japanese garden houses. The homogenous character of space can enhance plurality in use, where we cannot afford transformable building components.

The framework of adaptive architecture consists of drivers, elements of adaptation, methods, and strategies [1]. Change of function, capacity, or flow of an existing building drives the need to modify the existing organisation of the space. In addition to the climatic influence and site forces, the needs and values of the inhabitants shape the architecture. As a development strategy, it is necessary to keep the undetermined character of the spaces during design and construction to accommodate the users' needs over time. This character of soft use of the spaces is more prominent in the vernacular houses [6]. On the other hand, the architects define urban houses' spatial organisation, where the end-user is often absent during the development phase. The user's scope of personalised interpretation of space has been accommodated in some housing projects by architect Alejandro Aravena, constructing only half of the house at the initial stage [7]. This strategy ensured user participation through the later stages of development and made it financially viable. Some other aspects identified from terraced houses in London are transformable to contemporary houses: larger space, simplified construction technique, typical plan, and design for adaptability [6]. The simplified construction technique and the typical plan are also evident in the vernacular houses of Bangladesh. Urban areas need to accommodate multiple floors in a building and have structural challenges to achieve with simplified construction techniques. We can overcome this challenge using developed technology to enhance the simplified transformation of spaces in later phases by the user with limited skill related to building technology.

The study on the adaptability of residential architecture should incorporate its evolution, typology, and morphology. Researchers around the globe have adopted different criteria to study housing typologies. Physical attributes such as layout, density, degree of privacy, built area ratio, and structural system define some typologies [8]. In some other studies, social class, ownership type, and historical chronology are considered criteria to define typologies [9,10]. Historical chronology divided the building types into different categories according to timeline and style.

This study covered samples from different typologies according to physical, historical and social attributes. Six categories of vernacular rural house samples covered all broad categories traditionally developed in Bangladesh. Early urban houses were recorded with necessary drawings and the spatial features identified with the scientific method. This study can contribute as a reference document and very few other research on architectural detail of traditional houses in Bangladesh. The methodology used in this study developed from in-depth literature studies and examples around the world. Though the method is applied on selective samples from Bangladesh only, this structure can accommodate samples from other places.

Adaptive capabilities are the practical solution to the accommodation problem in the large metropolis, especially in developing countries with limited resources and capacities. However, adaptive architecture is not a new concept in residential architecture, as it has been widely practised in vernacular architecture. The lessons learned from them could eventually be adopted in the current architectural practice. This research aimed to determine the changing trends in the adaptive capacity of residential architecture. Therefore, the research objectives were to identify the relationship between adaptability and spatial parameters, conduct spatial analysis on adaptive characters, compare the adaptive characters of traditional and contemporary residential architecture, evaluate users' experiences and suggestions, and finally provide some recommendations on improving the adaptive capacities of the residential building.

1.1 Traditional Urban Residential Architecture

The evolution of urban residential architecture in Bangladesh can be distinguished into four periodical phases: (i) early urban dwellings in the 17th and 18th century, (ii) planned residential areas in the mid-20th century, (iii) walk-up apartments during post-independence and (iv) contemporary developer-built high-rise apartments [11]. These phases were also renamed based on their political contexts: (i) pre-colonial, (ii) colonial, (iii) pre-liberation and (iv) post-liberation architecture [12]. In the 17th and 18th centuries, the early urban dwellings followed a similar spatial layout and joint-family structure as the rural households, with three-court houses in relatively compact space. The outer court, a semi-public space, served as the entry court and was only shared by guests and male members. The inner court was rather more private and restricted to the female members and

close family members. The third court accommodated toilets and kitchen and acted as the service court, which was shared predominantly by the servants and non-family members [11]. In old Dhaka, shophouses with multi-courts could be found where the outer courtyard entertained domestic industries such as manufacturing and storing handicraft products [12,13]. Later in the mid-20th century, the urban middle-class generation had influenced the local government to initiate planned residential areas by allotting inexpensive plots for formal and gated single-family houses. Front courts were transformed into front lawns, and long corridors and dining spaces substituted the inner courts. Besides, the ancillary services such as toilets and kitchens were placed more attached to the house. After the independence, the transformation from joint-family to nuclear family and the demand for housing expansion resulted in separate gated houses on the same plot for the next generations and rentable walk-up apartments (up to four-storied) for additional income, abolishing the courts [11]. The condensed interior arrangement with smaller rooms and utilising dining space to connect the surrounding rooms provided the urban residents more affordability [12]. However, earlier low-rise residential buildings are being demolished in the contemporary period. Due to inflated land prices and the limited scope of horizontal expansions, the residents prefer the high-rise apartment complexes built by the developers. As a result, common spaces are shared by multiple families, unlike previous single-family residences.

1.2 Traditional Rural Residential Architecture

Several physical and social determinants characterise the diversified traditional rural settlements in Bangladesh. The physical determinants include geophysical location, land formation, climate, construction materials, and technology. On the other hand, religion, indigenous characters, defence, and cultural factors are the prime social determinants responsible for the evolution of the rural settlements [14,15] classified the rural settlements of Bangladesh into six typologies according to geophysical characteristics - (i) nucleated, and clustered settlements of northern Piedmont and the Barind regions, (ii) scattered settlements in the central delta region, (iii) linear settlements along the dying river in the moribund delta, (iv) dispersed and isolated settlements in the coastal areas and offshore islands, (v) very sparse and linear in the Eastern hilly region and (vi) high-density settlements in the haor basin (Islam, 2003). The hot and dry climate has geographically influenced the traditional architecture of the Barind region. The houses are mostly built of thick earthen walls to provide insulation and elongated shading devices [16]. The outer walls often have no opening; as a result, they develop an introverted character. The whole household is kept very dense and compact. Similar compact planning can be found in the haor basin due to the scarcity of elevated lands.

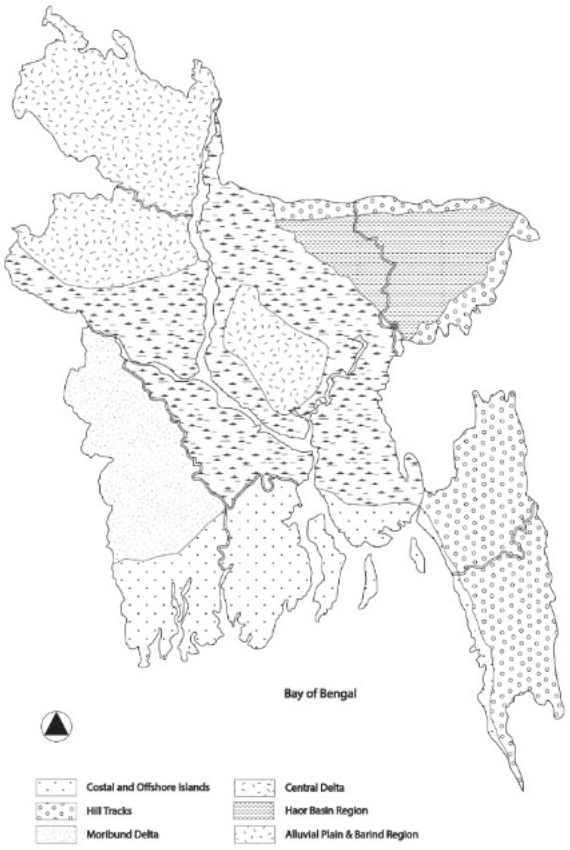

Figure 1. Diversity of rural settlements in the different geophysical regions of Bangladesh (Modified by the author from [15]).

Unlike Barind tract's mud houses, the haor basin's settlements are constructed with lightweight and perishable materials to withstand heavy rainfall. Diversity of materials and construction systems can also be found in central flood-plain where the dwellers prefer temporary materials and make-shift houses due to decaying during seasonal floods and river erosion. The sand bars and shoals there make it more difficult to establish permanent settlements without embankments. However, a more permanent structure is present in the moribund region due to the inactive delta formation. Settlements are planned there along the bank of the dying river in a linear order. Dispersed settlements are typical in coastal areas to encounter high wind exposure. Cyclone and tropical surges impact the built-forms and their orientation. The protective verandah, locally called 'pashchati', is a unique feature of coastal houses. On the other hand,

hilly settlements carry special architectural features. Their houses are built on elevated platforms to defend wild animals and strength from landslides and runoff. Their settlements are developed very sparsely nearby the freshwater sources. Instead of a traditional courtyard, every house uses a raised platform for harvesting and an additional flat surface. Their houses are richly affected by indigenous characters and their cultural factors.

2. Materials and Methods

2.1 Selection of Sample

The researchers initially selected several rural vernacular house-forms from six different geophysical regions of Bangladesh and four types of traditional urban house-forms. Later, a substantial number (nearly 70) of contemporary residences were selected and thoroughly surveyed. While selecting the contemporary residences, the researchers followed a balance according to the location and size of the floor area. Selected samples were located in four different socio-cultural and regional contexts: core urban areas, semi-urban areas, small townships, and rural areas. The size of the samples was categorised according to three general types: small (below $100m^2$), average ($100m^2$ to $180m^2$), and large (above $180m^2$). Irrespective of location and size, the researchers also balanced the ratio of professionally-built houses and DIY (do it yourself) houses for the diversity of the samples.

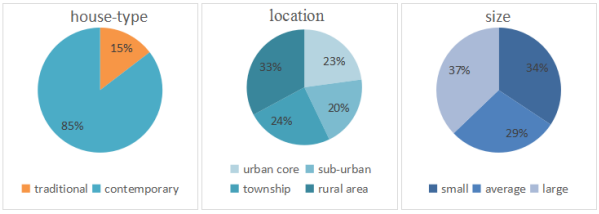

Figure 2. The ratio of samples according to house type, location, and size.

2.2 Data Collection

For the spatial analysis, the floor plan of selected houses was mostly recorded through physical and desktop surveys conducted during 2020-2021. The rest were collected directly from the professionals or the end-users. The documented floor plans were later analysed for spatial analysis. A questionnaire survey was also conducted to collect data on the variables related to current practice and adaptability, such as construction technique, involvement of end-user, and user experience.

2.3 Spatial Analysis

Spatial configurations such as degree of privacy, openness, generality and flexibility, functional sequence, and depth of space are closely related to adaptability. Therefore, our research is initially based on comparing these spatial configurations of traditional and contemporary houses and later identifying the changing trends using qualitative and quantitative measures. Space syntax is a widely used method for advanced spatial analysis in multidisciplinary fields, ranging from housing, retail environments, transport, and urban design to even human psychology, behaviour studies, sociology, criminology, and disaster mitigation [17,18]. Our research adopted this method as a supplementary tool for analysing spatial configurations in residential dwellings.

2.3.1 Degree of Privacy and Openness

Adaptability is inversely related to privacy. More private spaces are more rigid and thought to be less adaptive as they can not afford spatial alteration or modification without interrupting privacy. Semi-private and semi-public spaces are relatively more adaptable to an alternative use. Unlike privacy, the openness of a space is proportional to adaptability. In traditional houses, outdoors and semi-outdoors were more adaptable as indoor spaces could only accommodate more specific functions. The data on the degree of privacy and openness were prepared through visual analysis of the floor plan. They were later represented in a colour mapping. The plan analysis identified the ratio and changing characters between traditional and contemporary characters using a bar chart.

2.3.2 Generality and Flexibility

Generality is a property synonymous with universality, polyvalency or plurality [19,20]. The potential capacity to use a space for multiple purposes is termed generality. A singular space is restricted to a specific function only, whereas a general space can accommodate more inter-related activities, adding more adaptability, diversity, and flexibility. Similarly, flexibility is a characteristic that allows alterations and modifications within a space [20,21]. Flexible spaces are adaptable to any potential change in activities without interrupting the core functions. To collect data on generality and flexibility, the researchers prepared an extensive activity chart and studied the activities through functional sequential diagrams. The activity chart segregated the activities according to generality, flexibility, privacy, and openness. Later the generality and flexibility between the traditional and

contemporary houses were spatially and graphically compared.

2.3.3 Depth Map

The relation between adaptability and the depth of space is rather indirect. A shallow plan is considered less complex and has more simplified connectivity. Shallow spaces can accommodate more generalised and shared functions. On the contrary, deep spaces are often singular and monovalent as they are primarily designed for specific and private activities. Therefore, more depth of space can reduce the generality, thus diminishing the adaptability. Less depth of space is counted as more adaptable. Depth of space was measured through node analysis with convex mapping and justified graph. Convex spaces are visually barrier-free sub-spaces within a room where any straight line connecting two points does not intersect its perimeter [20]. Convex spaces in residence are generally connected through a doorway or an opening. Convex mapping displays the typicality and shape of the space, whereas a justified graph only shows connectivity. The justified graphs consist of nodes and lines. The nodes and the line respectively denote the convex spaces and connectivity. Justified graphs were produced using AGRAPH software, a spatial tool developed by Manum, Rusten, and Benze (2005) and Manum, Rusten (2009) for analysing nodes and connectivity [22,23].

2.3.4 Typicality

Simplicity and similarities in floor plan, room size, shape, and connectivity are referred to as typicality. A uniform structural grid, convex space, and open floor plan can also accelerate the typicality of a space. Typicality is opposite to uniqueness, according to Rem Koolhaas, as typical architecture has no specificity [6]. It is easily adaptable because its activities could easily be replaced or altered with another typical room. Typical rooms are economical and easily constructible. A simple convex mapping and visual analysis of the plans of different house types was conducted in terms of size, shape, opening, and overall configuration to identify the rooms with similar spatial attributes.

2.4 Survey and Non-spatial Methods

The information on socio-cultural aspects of residential developments was recorded from the survey. There are many factors that cannot be directly identified from the visual features of the house. For example, the construction technique can be identified, but the residents' level of knowledge on that technology is collected through a questionnaire survey. The survey also identified the involvement of the end-users at the construction time. Their reflection on the usability and adaptability of the house is recorded here.

2.4.1 Construction Technique and Adaptability

Construction technique has a significant impact on adaptability since it can limit the user's scope of modification or expansion of space in later stages [6]. 'Hard technology' adopted by the engineers and architects during construction time is the main reason. Though it does not mean the advanced construction techniques are always 'Hard technology'. Modular design, prefabricated building elements, and modifiable components can significantly enhance the house's adaptability [3]. Surface, module, spatial features and technical systems support the adaptation process [1]. These issues have been analysed in selected samples of traditional and contemporary houses. The adaptability of the traditional houses was possible with simple construction techniques. With the change in need and context, taller residential buildings became necessary to fulfil the housing demand. Though it is not possible to use the same simple techniques in most contemporary buildings, transformative building components can ensure the adaptability of contemporary residential apartments [24].

Construction technique, use of local materials identified from the physical survey and literary evidence recorded to define the level of adaptability of different study samples (Figure 3). Some contemporary rural houses are still using traditional materials and construction techniques. However, urban house construction has changed drastically in recent years. So we could not collect the construction photos of the traditional urban house, but we acquired some idea from the literature study and physical evidence from surveying the old buildings. Many rural houses also use modern construction materials and advanced techniques these days. The existence of traditional and contemporary rural houses in the same compound is presented in the bottom left picture of Figure 3. Urban multistoried building construction was surveyed to record the highly used construction technology of the present time.

2.4.2 Involvement of End-user

Tenants of the houses are not always involved during the development phase of the building. Especially in contemporary houses, many of the tenants buy ready apartments according to their needs. Involvement of the inhabitants is a significant issue to enhance houses'

Traditional rural house construction with bamboo, thatch, wood and tin. Source: Author

Traditional urban houses, made of brick and plaster Source: Architect Mithun Chandra Nath

Contemporary rural houses, made of brick and concrete. Source: Architect Mithun Chandra Nath

Use of heavy equipment in contemporary house construction. Source: Author

Figure 3. Change in construction technique of traditional and contemporary house

adaptability [1,2]. Architects can keep an opportunity for future inhabitants to further develop the houses in later stages to accommodate their changing needs with time. It is not about a perfect design at the beginning but creating a framework for an efficient layout to guide the development over time that allows the further contribution of the users. Social housing in Chile, designed by architect Alejandro Aravena provided half of the house constructed initially and the rest of the spaces to be developed by the user at the later stage [7].

In the selected contemporary house samples, the participants responded to their involvement during the design and construction of the time. The questions regarding the rented, bought, or personally developed house reflected the involvement of the end-users during the development process. Some participants also reflected their views in the open-ended questions regarding the scope of involvement in this process. We also identified the houses designed by professionals and found a significant number of houses actually designed by the owners themselves. They also answered the question regarding knowledge and personal skill on construction techniques used in their own house.

2.4.3 User Feedback

One hundred sixty-seven residents responded to the questionnaire survey regarding the adaptability of their own house. We tried to collect responses from male and female users to get a complete picture. The samples were divided into three types according to the size of the residential unit: up to 800 square feet categorised as the small unit and above 1800 square feet unit size classified as the large unit. The rest of the units are considered mid-sized residences. In the survey, one-third of the participants were female, and small residential units were fewer (Figure 4).

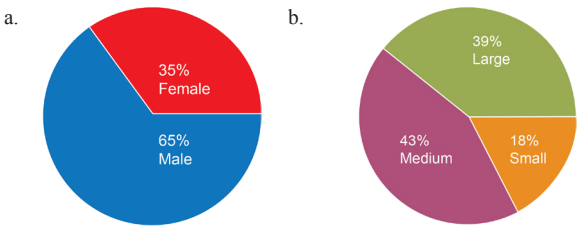

Figure 4. Ratio of female and male participants (a), the ratio of small, medium and large size units owned by the participants (b)

We have conducted the survey during the pandemic lockdown period to compare the use pattern of different rooms in normal situations and pandemics. Due to the lockdown situation, the same space was used for additional functions like home office and online education. This situation helped the inhabitants to evaluate the possibility of using the space for alternative use. They identified the spaces with high adaptability, where they could perform new types of activities that were not necessary for regular situations. The participants also identified the spaces where the activity pattern was not changed due to lack of adaptability and dedicated functional use of the particular space. They also reflected on the existing volume of different spaces and possible changes in the scale of those

spaces to improve the adaptability of the house. It helped us determine the priority of end-users.

3. Results

3.1 Spatial Analysis

In this section, we have analysed the study samples in terms of spatial quality. Selected residential house types from six rural areas and three traditional urban house types were analysed in the first step to get a comparative idea on the degree of openness, multifunctional use of different spaces and simplicity of the house plan in terms of spatial configuration and connectivity. In the 2nd stage, contemporary houses from 4 different settings were analysed with the same method. The types used here are rural, small town, fringe area of city, and core city. 4 typical samples were selected from 70 selected samples within these four categories and presented in the analysis stage.

3.1.1 Change of Privacy and Openness

Openness and degree of privacy followed a changing trend in traditional and contemporary houses. Figure 5 shows that openness was prominent in traditional rural and urban dwellings, particularly hill tract houses. In those houses, openness was provided by courtyards, backyards, lawns, gardens, ponds, etc. Indoor spaces were limited to 20% in most traditional rural houses except in the Barind tract, where the compact arrangement due to climatic considerations resulted in nearly 30% indoors. The ratio of indoor spaces had a surging trend in most traditional urban dwellings. Moreover, semi-outdoor spaces have traditionally featured in the Barind tract, haor basin, and coastal houses to a greater extent and existed in the hill tracts and from early to post-independence urban houses to a lesser extent. These spatial arrangements enhanced adaptability in the traditional dwellings.

On the other hand, openness is outrageously neglected in contemporary dwellings due to the densification of house plans and forms (Figure 6). Consequently, the degree of privacy was gradually rising as dwellers preferred invisible partitions and separate rooms for adolescents and children. Semi-private and semi-public spaces in residential buildings, such as prayer rooms, family temples, study rooms, restrooms, verandah, etc., were dominantly placed into more private zones. Smaller outdoor spaces like open balconies, terraces, and roof gardens substantially replaced the larger outdoor areas such as courtyards, lawns, and gardens. Due to strict building codes in metropolitan urban areas, at least 25% of outdoor and percolated green space has been provided recently, albeit mostly in peripheral or non-usable areas. The near-extinction of semi-outdoor spaces in contemporary houses was one of the most significant changes found. As a result, adaptability was significantly reduced in contemporary dwellings.

3.1.2 Changes in General and Flexible Spaces

The activity chart in Figure 7 clearly showed that the number of indoor activities had surged immensely in contemporary houses. Most outdoor and semi-outdoor activities in traditional dwellings were later occurring indoors in recent houses. In traditional houses, the courtyards were the most generic space. Multiple social (recreational activities, festivals, and social gatherings), economic (harvesting, animal farming, gardening, etc.), and domestic (cooking, bathing, drying, etc.) activities took place. These activities in the courtyards could also be altered or transformed according to the user's preference and temporal, diurnal, and seasonal changes. Therefore, they also had more flexible characters. Besides, the semi-outdoor verandah was another polyvalent space that accommodated numerous formal and informal activities such as meetings, family gatherings, dining, resting, studying, cooking, craft-making, etc. Sleeping and storing were the only notable specific activities that were held indoors. Lately, in contemporary houses, most formal and domestic activities such as meetings, dining, cooking, bathing, etc., were held indoors instead. The neighbourhood streets in the small towns and rural areas and the rooftop terraces in the urban and semi-urban regions became the only place for social gatherings. The indoor spaces in the urban and semi-urban apartments were more specific, except the dining spaces that could be conditionally and occasionally considered the only generic space there. As a result, those contemporary apartments were deficient in flexibility and generality than their traditional counterparts.

3.1.3 Transformation of Connectivity and Depth

The justified graphs in the depth analysis (Figure 8) found that the mean step depth in traditional houses was relatively lower than in contemporary apartments. Mean depth had been moderate and limited to 4-5 steps in the rural houses except in the Barind tract and haor basin because of their consolidated and compact house plan. Besides, the internal rings or bypass connectivity, instead of corridor-type connectivity, could be found in the rural houses of Barind, haor, coastal and hilly regions. In most rural houses, courtyards were the most accessible

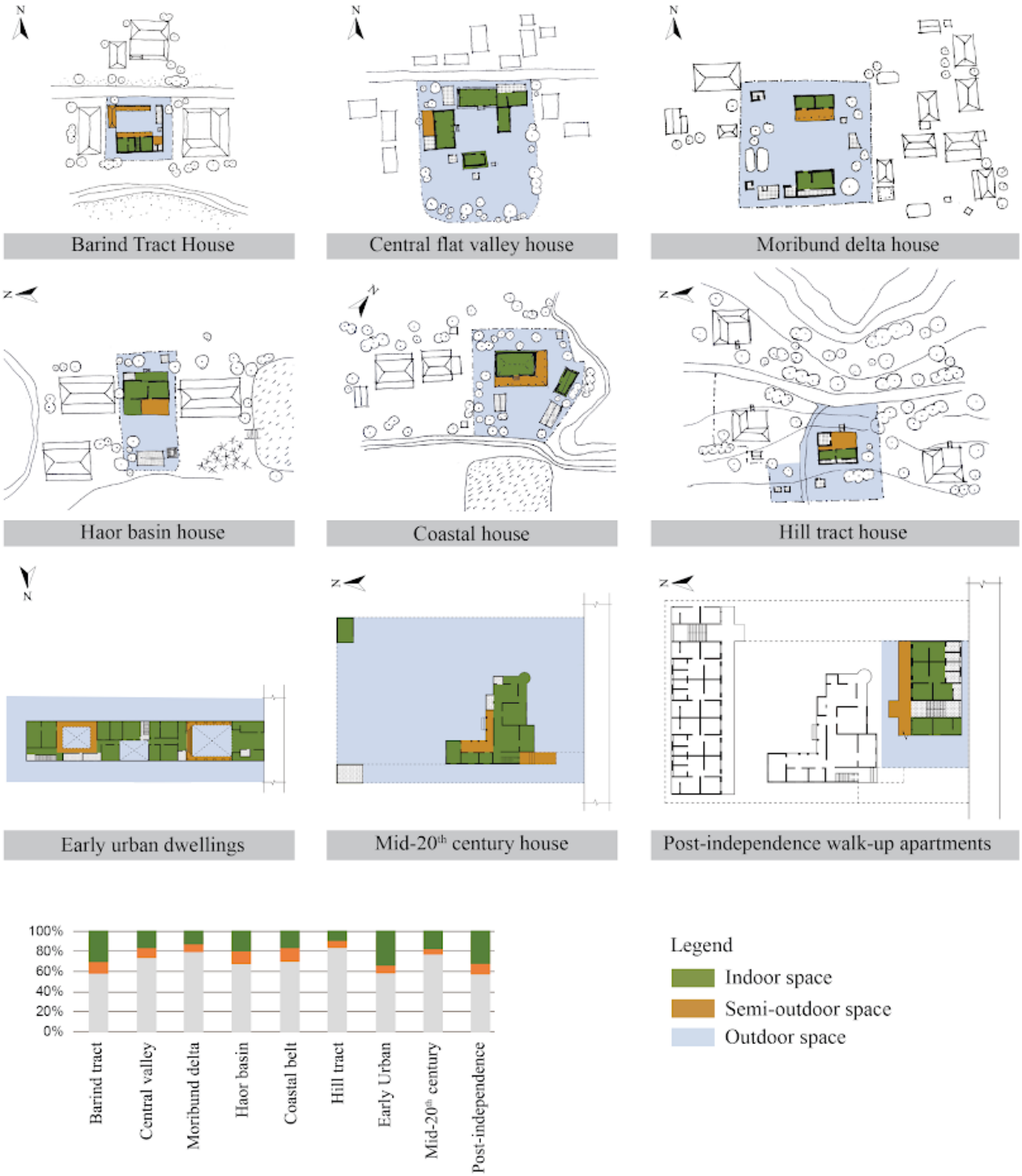

Figure 5. The ratio of openness in traditional rural and urban houses (Urban house plans modified by author from [11,12].

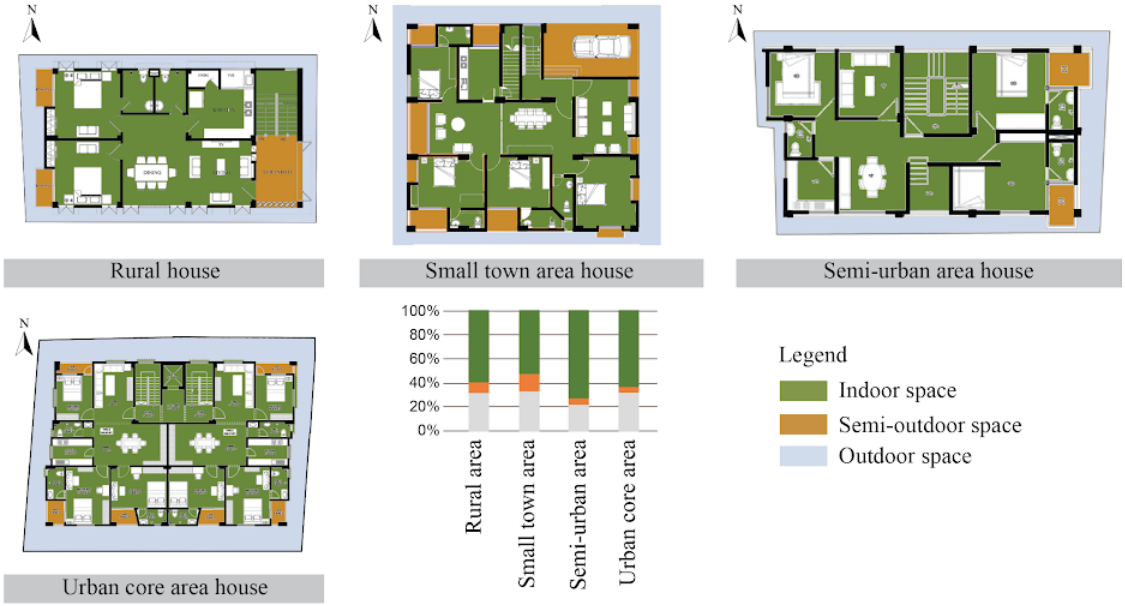

Figure 6. The ratio of openness in contemporary houses.

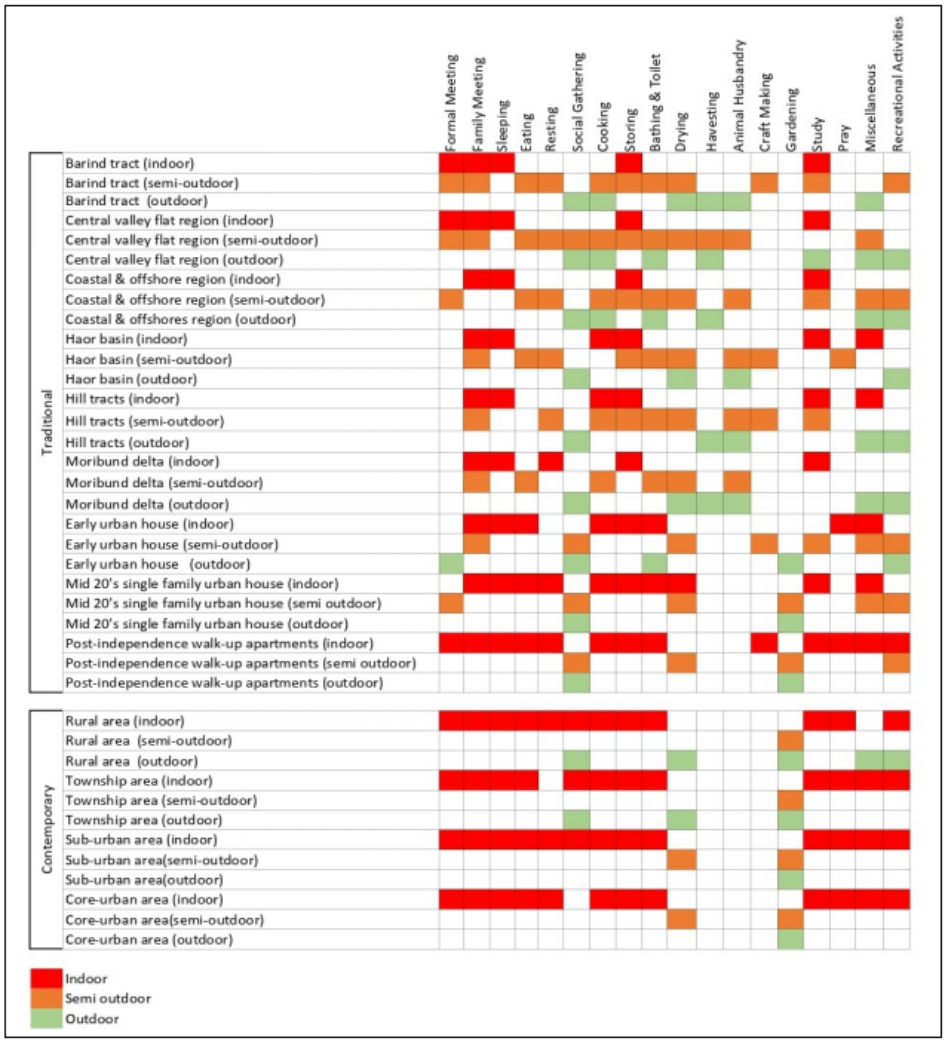

Figure 7. The activity chart in traditional and contemporary houses.

and focal point, connecting nearly 4-8 other individual spaces. Later in the traditional urban dwellings, the mean depth was slightly surged to accommodate more private and isolated rooms. Corridor-like connectivity was introduced to connect those isolated rooms as in the post-independence walk-up apartments. Both corridors and internal rings were present in the mid-20th century single-family houses. Eventually, the mean depth had increased to an average of 6-8 steps in contemporary apartments. The dining space became the most interconnected space instead of courtyards. Excessive use of corridors in rural, semi-urban, and core urban houses was found, as internal rings were rarely used and limited to townhouses. Cul-de-sac or isolated spaces had dominated contemporary dwellings. Those isolated spaces were generally used for specific and private activities. Overall, spaces connected by internal rings were more flexible than spaces connected by corridors or cul-de-sac spaces. Therefore, generality and adaptability were comparatively less in contemporary houses.

3.1.4 Decreasing Trend in Typicality

Typicality in the contemporary urban houses followed a distinctive changing trend. Traditional houses had prototypal rooms and minor variations in plan within the same region. As shown in Figure 9, the ratio of convex spaces was more in the rural house plans. The rooms were more simple and uniformly shaped. The structural grids were almost similar, and structural members were located in the peripheral walls, making an open internal floor plan. Nearly 60%-80% area in the traditional rural dwellings was typical and easy to adapt. Among them, coastal houses showed the most uniform and adaptive character that helped them to survive climatic vulnerability. In contemporary rural and urban houses, the ratio had drastically dropped below 40%. The floor plans had lost their open character as partition walls, and structural members divided the internal space into smaller sub-spaces. Besides, as the types of rooms had increased, the rooms were built of different shapes and sizes. Structural grids were also not similar inside, making the interior spaces less flexible and adaptable.

3.2 Survey Data Analysis

In this part, we have presented the survey findings and non-spatial type of analysis. Socio-cultural dimension of housing included with simple illustration and chart. The user feedback from the survey was also analysed to identify the residential spaces people are using for diverse functions and the spaces with low capacity to accommodate multiple activities.

3.2.1 Changes in Construction Technique

Most of the rural houses involved vernacular material and construction techniques in the past (Figure 10). Traditional rural houses could be built, repaired and maintained easily by the inhabitants. The contemporary rural house also includes factory-made material and advanced construction techniques to cope with the increased demand. At the same time, the scope of further development by the end-user at later stages became difficult. Even in rural areas, most of the inhabitants have minimal knowledge about their own house construction. Almost everyone had some construction skills using the vernacular materials in the past.

On the other hand, the urban houses used complex construction techniques and heavy equipment for house construction. General people cannot avail this type of facility to construct or repair their own house. Only skilled workers can build urban houses. This scenario is more complicated now—professional developer companies taking charge of construction in most multistoried houses. Especially the high-rise residential buildings became necessary in large cities to meet the housing demand. The current practice in the housing market of Bangladesh does not allow further modification of residential units of these multistoried buildings. So the adaptability of spaces is significantly low these days.

3.2.2 Changing Trends in the Involvement of End-user

In the past, most rural people had the essential skills in constructing their houses and traditional knowledge about house planning. This traditional knowledge included the thumb rule of room size, structure made of vernacular materials, and the basic planning of the residential units. The user could plan and construct the houses at later stages when any expansion or modification was necessary. The construction technique in the urban area involved skilled labours with comparatively advanced technology and material. The design and planning were according to the need and guidance of the owner and assisted by professionals. Though the end user's involvement was not possible, the owner was the leading decision-maker of the design. In the contemporary period, houses in rural areas still involve most end-users in the design decision-making process. However, due to the use of factory-made building materials majority of the rural houses are being constructed by hired masons. A very few general users still have the skill to construct their housing due to using

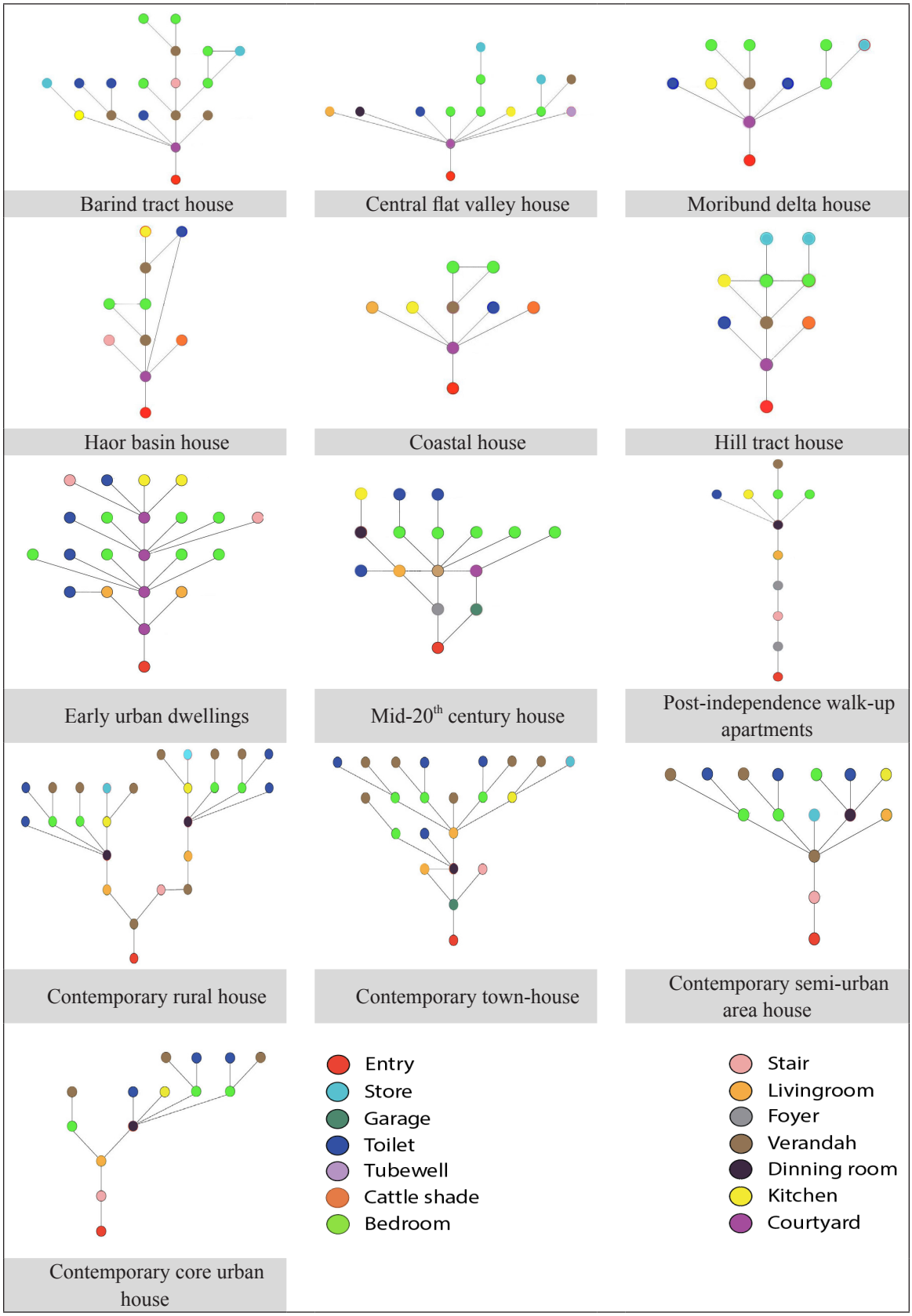

Figure 8. The J-graph in traditional and contemporary houses.

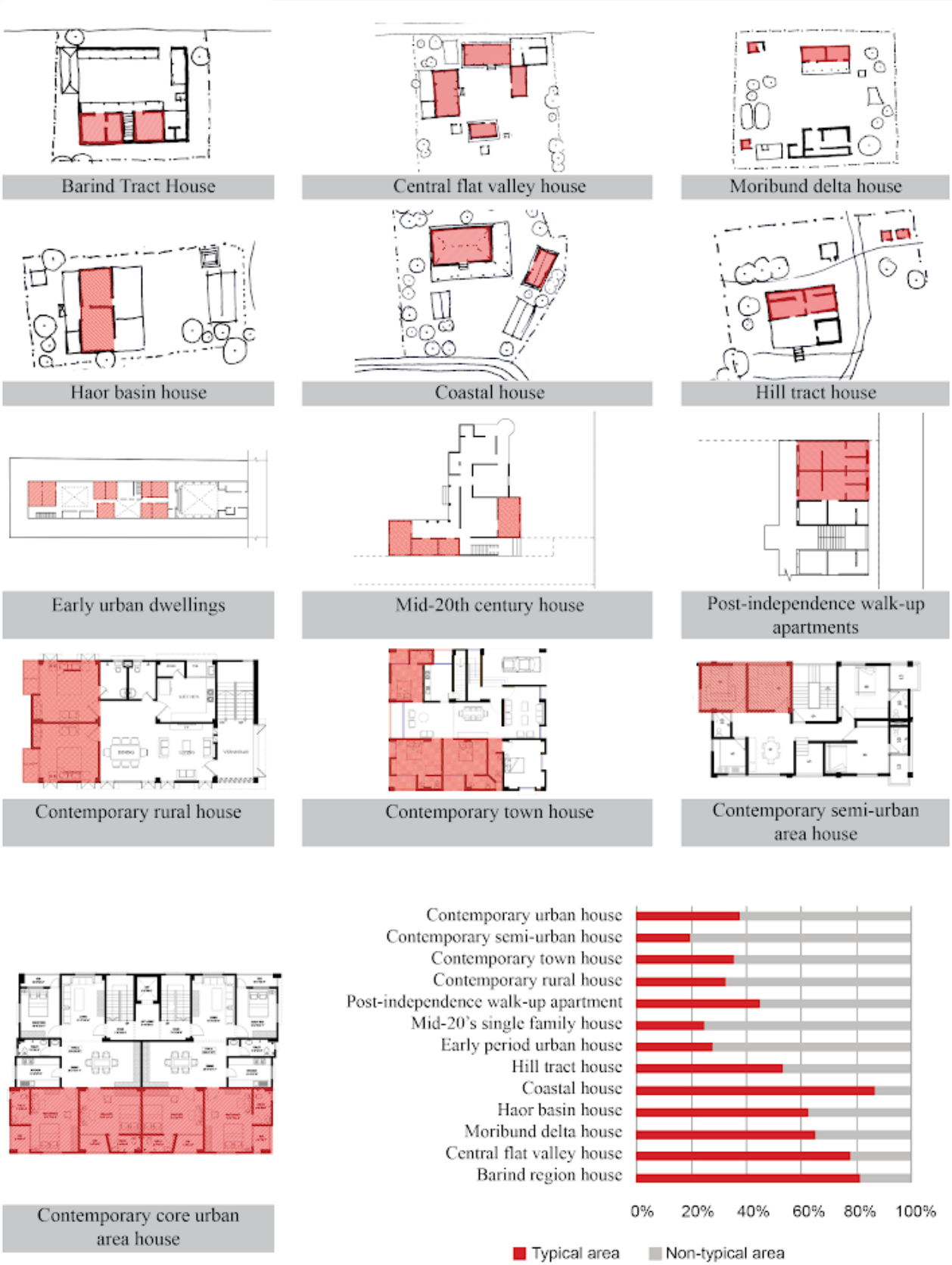

Figure 9. Typical spaces in traditional and contemporary houses.

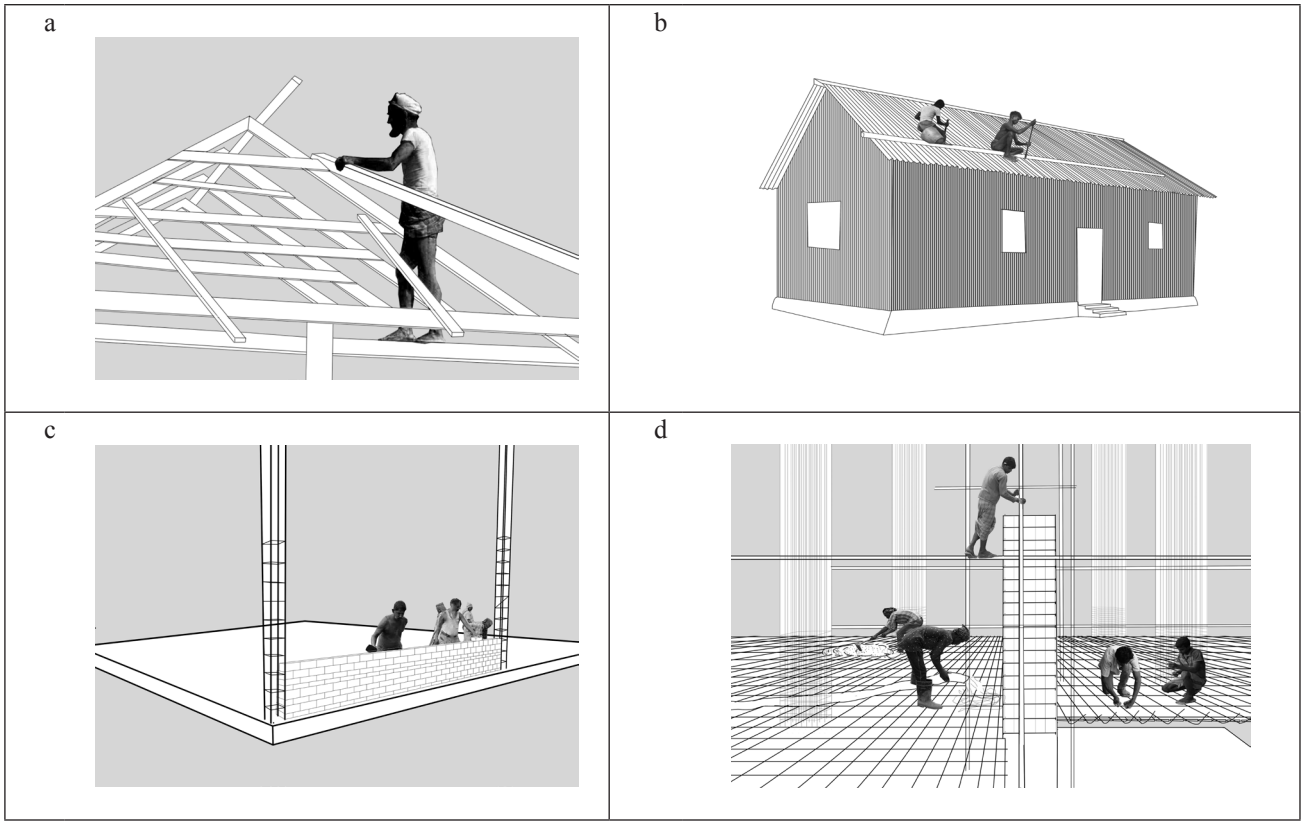

Figure 10. Construction of traditional rural houses (a, b) Contemporary rural house (c) and contemporary urban house (d)

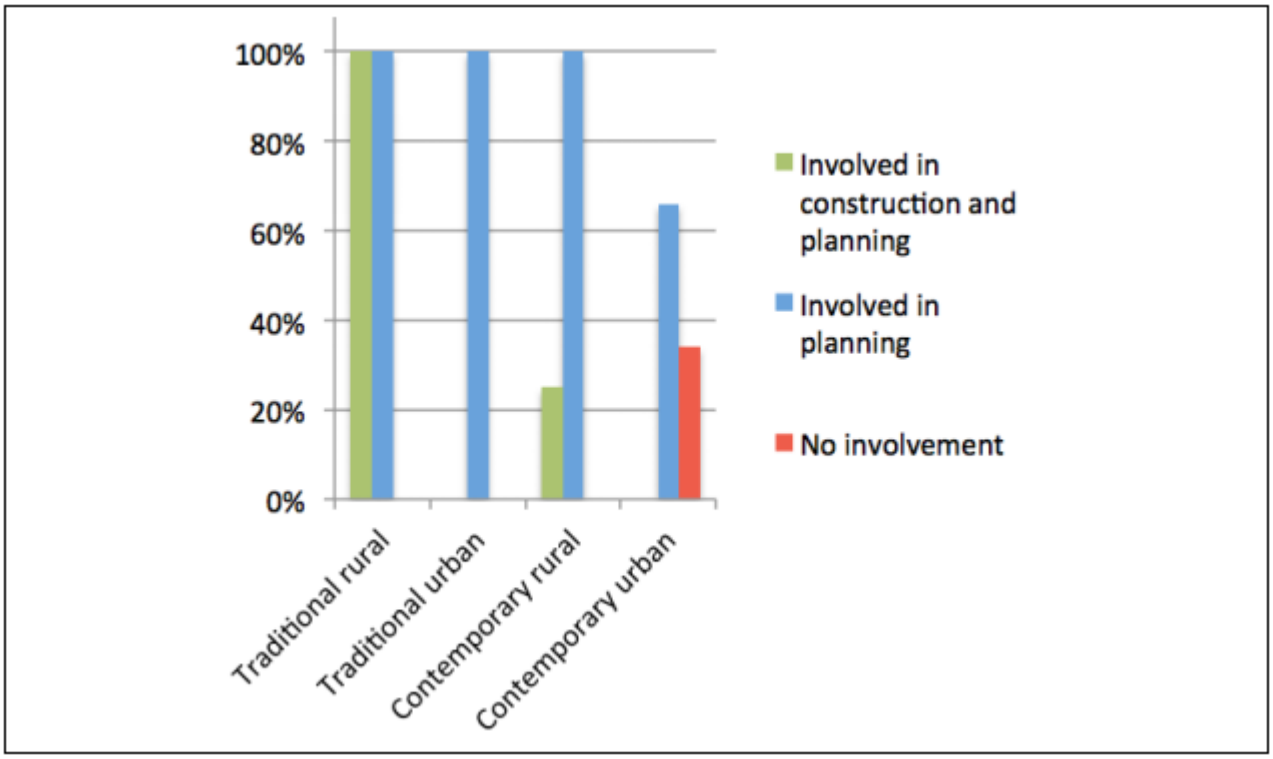

Figure 11. Different levels of involvement in traditional and contemporary house development in rural and urban areas.

complex modern construction techniques. Excluding the slums, the formal houses are always built by skilled professionals in the urban areas. Even in some cases, the ultimate user of the housing units is unknown until the construction is completed. Almost one-third of the study samples from the contemporary urban category were rented or sold to a user who can choose if the housing unit satisfies his need for space but cannot participate during the design phase or make any adjustment during their stay. Figure 11 shows a significant decrease in the involvement of end-users in the design and development works of contemporary houses.

3.2.3 User Feedback and Identification of Scopes

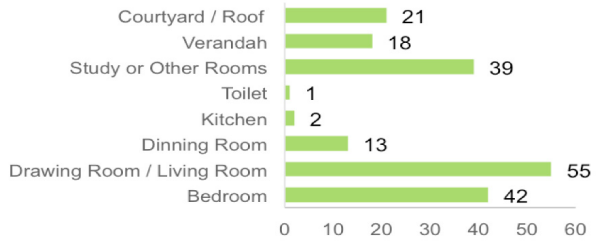

Figure 12. Spaces with high adaptability

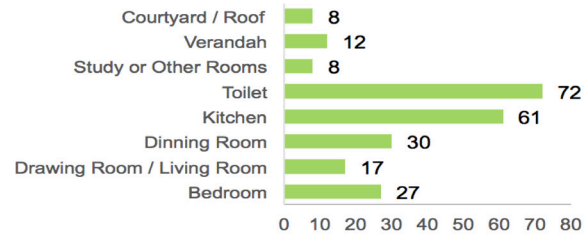

Figure 13. Spaces with low/ no adaptability

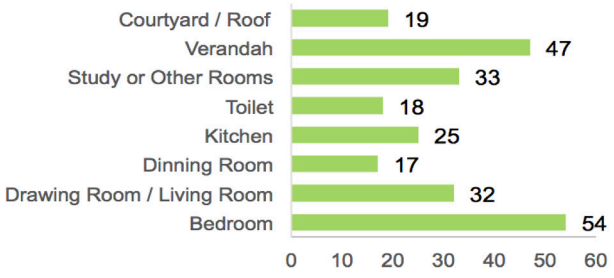

Figure 14. More spaces to be allocated at these areas for better adaptability

According to the survey feedback from inhabitants, the living room was the most adaptable space in the home that accommodated the most diversified types of functions, especially during the pandemic period (Figure 12). The bedroom was the second most adaptable space where online class and home office activities had taken place, especially for the small houses with no study room or family living space with adequate privacy when required. If there was a study space, then this type of function mostly took place there. On the other hand, spaces for dedicated service functions like kitchens and toilets were the least adaptable space (Figure 13). Predictably, these types of spaces can not host diverse functions. Outdoor spaces are not much available in contemporary houses. Roofs are the alternative to ground-level open spaces for typical urban houses. A considerable number of users had identified open spaces like courtyard or roof and semi-outdoor spaces (veranda) as spaces with adaptability. We had also asked the participants' opinions on where to allocate more spaces to achieve better adaptability. Bedroom, living, study room received the highest importance among the interior spaces (Figure 14). Semi-outdoor spaces also received high-level importance to allocate larger spaces. From the open-ended question part on how to make the houses better in terms of living conditions, the importance of semi-outdoor spaces had obtained a high priority. This is not only for the possible multipurpose use but also to increase the openness of the living units to invite nature and enhance livability.

4. Discussion and Recommendations

According to spatial analysis and survey feedback, semi-outdoor and outdoor spaces can enhance adaptability. Due to high land prices and space limitations, it will be challenging to provide ground level open courtyards or gardens. In that case, the roof should be utilised as an open space. Roof gardening has already become popular. The local government is also supporting this type of initiative with reduced holding tax and other incentives. Since the residential building density is much higher, the multistoried multifamily apartment cannot satisfy all the needs of individual residents only with the roof level community space. Open terraces and an adequate number of semi-outdoor spaces should be provided at different levels of multistoried residences. Comparing the contemporary residences, we found that the proportion of open spaces are higher in core city area compared to other urban areas. Statutory building guidelines ensured at least 20-25% green space at each residential plot. In addition to this green area, other community spaces and paved open spaces are also ensured in this type of house. Integrated design of these outdoor spaces in residential zones can enhance the living standard more.

The indoor spaces with modular structural grid, simple circulation layout and adaptable zoning of service functions can enhance adaptability. Especially for multistoried buildings, the position of service cores is important to enable diversified plans at a different level. The spatial arrangement of the residential units reflected through depth map analysis indicated that effective use

of common spaces as nodes could simplify the linkage. Architects should analyse the plan using a depth map to identify the level of simplicity in terms of functional linkage and further improve it.

The typicality of rooms in terms of size and configuration will increase the capability of transforming one functional space into another functional use. It can be further enhanced with the use of transformative building components. With the introduction of modern building technology, we lost the opportunity of transforming building components by the residents on their own. Practically we cannot start using the vernacular methods, and the inhabitant cannot acquire the traditional construction skill. Instead, using factory-made transformative building components like a movable wall, operable building façade, and expandable floor slabs will be useful to increase adaptability. Prefabricated building components with multiple assembling options can enable the users to choose the components according to their needs. This type of element can be attached or detached from core building components to allow changing the volume of space if necessary.

Apartment developers dominate the contemporary housing market in the cities. The prospective residents of those apartments get involved after the design of the residential units has been finalised. In most cases, the consumers choose from the already constructed building. In fact, the ready apartments are gaining more popularity, though they fail to satisfy the user demand fully. The business model of the apartment type housing market should be reshaped to enhance the participation of end-users in the design and development process and thus enhance adaptability.

5. Conclusions

Global climate, housing policies, real estate economy, and construction technology - all these sectors have experienced drastic changes in recent years. Besides, during the current covid-19 pandemic, the healthcare and communication system has also undergone massive rethinking and restructuring. Architecture should also evolve with these social, technical, and environmental changes. The capacity to transform according to time, user's need, and environment are regarded as adaptability. Architecture should be adaptive during post-occupancy diagnosis and retrofitting of buildings to sustain for more extended periods. Adaptive architecture is more flexible and durable. Therefore, it is ultimately cost-effective in the long term. Besides, it can provide a permanent solution to complex housing problems in developing countries, as it is time and space-saving. The adaptive architecture allows the end-users to participate in the design development phase directly. Lessons from traditional architecture also indicated the implementation of adaptive capabilities. The traditional architecture was more sustainable and long-lasting because of its inherent adaptive capacities developed through the users' needs, skills, and experience.

On the contrary, real estate agencies dominated the contemporary housing sectors. Their typical apartments for mass production were not environmentally responsive and socially communicative to the gradual changes in the behaviour pattern and needs of the end-users. This research focused on identifying the differences of adaptive characters of traditional and contemporary residential architecture. The research methodology adopted both spatial and non-spatial analysis. Spatial measures searched the relation of adaptability with privacy, openness, connectivity, depth, typicality, and flexibility. Non-spatial measures searched for construction techniques and involvement of user groups in the design development phases. In parallel, the researchers conducted a questionnaire survey to communicate with the end-users and collect their responses and suggestions. The changing patterns of adaptive measures were evident in both spatial and non-spatial analysis of traditional and contemporary houses. The contemporary houses showed a significant drop in openness, typicality, and flexibility. The degree of privacy and mean depth of space had unexpectedly risen. Even the design development and construction process excluded the users as the construction technology experienced massive overhaul and became more complex for the native users. Eventually, the building and the users were losing their adaptive capabilities, which was a prime concern of this research. The researchers recommended several suggestions to overcome this concern. Further research on the sustainability parameters of adaptive architecture could prove influential in solving this problem.

Author Contributions

The 1st author contributed in developing concepts, methodology, and analysis. The 2nd author assisted in methodology and analysis and the 3rd author contributed in survey analysis and illustrations.

Conflict of Interest

The authors declare no conflict of interest.

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References

[1] Schnädelbach, H., Adaptive Architecture: A Conceptual Framework. In Proceedings of Media City: Interaction of Architecture, Media and Social Phenomena; McQuire, S., Eds.; SAGE Publications: Weimar, Germany; 2010; pp. 532-555.

[2] Schneider, T., and Till, J., 2005. Flexible housing: Opportunities and limits, Architectural Research Quarterly. Vol. 9, Issue 2: pp. 157-166. DOI: https://doi.org/10.1017/S1359135505000199.

[3] Slaughter, E. S., 2001. Design strategies to increase building flexibility, Building Research and Information. Vol. 29, Issue 3: pp. 208-217. DOI: https://doi.org/10.1080/09613210010027693.

[4] Amini, M., Mahdavinejad, M., and Bemanian, M., 2019. Future of interactive architecture in developing countries: Challenges and opportunities in case of Tehran, Journal of Construction in Developing Countries. Vol. 24, Issue 1: pp. 163-184. DOI: https://doi.org/10.21315/jcdc2019.24.1.9.

[5] Groák, S., The Idea of Building: Thought and Action in the Design and Production of Buildings; E & FN Spon: London, UK, 1992; pp. 15.

[6] Till, J., & Schneider, T., 2005. Flexible housing: The means to the end, Architectural Research Quarterly. Vol. 9, Issue 3-4: pp. 287-296. DOI: https://doi.org/10.1017/S1359135505000345.

[7] Evenko, M. G., & Doroginin, Y. V., 2020. Modern social housing, IOP Conference Series: Materials Science and Engineering. Vol. 913, Issue 3: pp. 1-7. DOI: https://doi.org/10.1088/1757-899X/913/3/032018.

[8] Gokce, D., and Chen, F., 2018. A methodological framework for defining 'typological process': the transformation of the residential environment in Ankara, Turkey, Journal of Urban Design. Vol. 24, Issue 3: pp. 469-493. DOI: https://doi.org/10.1080/13574809.2018.1468215.

[9] Remali, A. M., Salama, A. M., Wiedmann, F., and Ibrahim, H. G., 2016. A chronological exploration of the evolution of housing typologies in Gulf cities, City, Territory and Architecture. Vol. 3: pp. 1-15. DOI: https://doi.org/10.1186/s40410-016-0043-z.

[10] Kowaltowski, D., Labaki, L., Pina, S., Monteiro, E., Júnior, J., Oliveira, M., and Moreira, D., Attitudes towards open and communal space in housing: analysis of typologies in the state of São Paulo, Brazil. In International Symposium of IAPS CSBE - Social Change and Spatial Transformation in Housing Environments; The Faculty of Architecture Press: Istanbul, Turkey, 2005; pp. 51-62.

[11] Ahmed, Z. N., 2009. Globalisation and Architecture: reflections of shifting lifestyles in Bangladesh, Protibesh: Journal of the Dept. of Architecture, BUET. Vol. 13, Issue 1: pp. 17-28.

[12] Khan, S., 2020. Spatially Adaptive Courtyard Models for High-Density, Multistoried Residential Developments in Bangladesh. Master's dissertation at Pennsylvania State University. Retrieved at: https://etda.libraries.psu.edu/catalog/18262ssk211 [accessed 21.06.2021].

[13] Imamuddin, A. H., Hassan, S. A., and Alam, W. Shakhari Patti: A Unique Old City Settlement, Dhaka. In Architectural and Urban Conservation in the Islamic World; The Aga Khan Trust for Culture: Geneva, Switzerland, 1990; pp. 121-132.

[14] Islam, A. K., 2003. Patterns and Changes of Vernacular Architecture in Bangladesh: An Application of Amos Rapoport's Theory Defining Vernacular Design. Master's dissertation at The Royal Institutes of Technology: Stockholm, Sweden. Retrieved at: https://arc456.files.wordpress.com/2015/02/msc-thesis-kausarul.pdf [accessed 21.06.2021].

[15] Choudhury, M. I. & Zaman, M. A., 1976. Settlement Pattern and Special Problems: National Report on Human Settlements, Bangladesh. In Habitat, United Nations Conference on Human Settlements, Vancouver: Canada.

[16] Polin, F., 2018. The Changing Pattern of Mud Houses in the Barind Region of the Changing Pattern of Mud Houses. In the Fourteenth International Conference on Healthy Houses, Brno University of Technology: Brno, Czech Republic.

[17] Hillier, B. & Hanson, J., 1984. The social logic of space. Cambridge University Press: Cambridge, UK. DOI: https://doi.org/10.1017/CBO9780511597237.

[18] Rahman, M.A., 2021. Optimising the spatial configurations of an urban open space: syntactic analysis of the restored Hatirjheel wetland, Dhaka, Acta Sci. Pol. Architectura. Vol. 20, Issue 2: pp. 3-16. DOI: https://doi.org/10.22630/ASPA.2021.20.2.10

[19] Leupen, B., 2006. Polyvalence, a concept for sustainable dwelling, Journal of Nordic Architectural Research. Vol. 19: pp. 23-31. Retrieved at: http://arkitekturforskning.net/na/article/view/156 [accessed 21.06.2021].

[20] Femenias, P. and Geromel, F., 2019. Adaptable housing? A quantitative study of contemporary apartment layouts that have been rearranged by end users, Jour-

nal of Housing and the Built Environment. Vol. 35: pp. 481-505.
DOI: https://doi.org/10.1007/s10901-019-09693-9

[21] Cold, B., Gunnarshaug, J., Hiortøj, E., and Raaen, H., 1984. Nye boligformer, en eksempelsamling [New forms of dwellings, a collection of examples in Norwegian]. Tapir: Trondheim, Norway.

[22] Manum, B., Rusten, E. and Benze, P., 2005. AGRAPH, Software for Drawing and Calculating Space Syntax Graph. In Proceedings of 5th International Space Syntax Symposium, TU Delft: Delft, Netherlands. Vol. I: pp. 97. Retrieved at: https://www.ntnu.no/ab/spacesyntax/ [accessed 21.05.2021].

[23] Manum, B. and Rusten, E., 2009. AGRAPH; Complementary Software for Axial-Line Analyses. In Proceedings of 7th Space Syntax Symposium; Daniel Koch, Lars Marcus and Jesper Steen, Eds.; KTH: Stockholm, Sweden, 070:1. Retrieved at: https://www.semanticscholar.org/paper/AGRAPH-Complementary-Software-for-Axial-Line/c2d9dad964398e96c87550ee52bc11836fc303ae [accessed 21.05.2021].

[24] Andjelkovic, V., 2016. Transformation principles in the architectural design of a contemporary house, ArchiTECT. Vol. 4, Issue 1: pp. 86-107.

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ARTICLE

Thermal Impacts of the Internal Courtyards in Compound Houses: The Case of Tamale Metropolis

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ABSTRACT

The research seeks to understand the effects of internal courtyards on thermal comfort conditions in compound houses in Ghana's Tamale Metropolitan area. Internal courtyards are an integral part of the design of compound houses in this location.
Their inclusion in building designs is largely as a point of domestic activity such as cooking and cleaning and also for social interaction. However, a lot of interchanges in thermal conditions between structures and the outdoors take place within these internal courtyards. Various design details of the building will engender different thermal responses of the internal courtyard. This paper assesses thermal comfort in compound houses as against bungalow type houses in the Tamale Metropolis, Ghana by the application of the Predicted Percentage of Dissatisfied Persons (PPD) and Predicted Mean Votes (PMV) model. This prototype compares with the International Standards Organization (ISO) 7730 and American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 55 (estimated values between 23˚C - 26˚C seen as the allowable temperatures). Ambient indoor conditions (dry bulb temperature and relative humidity) of five (5) buildings each from the two building typologies from were recorded over a period of ten calendar months. These ambient conditions were analyzed, consequently generating the Predicted Percentage of Dissatisfied Persons (PPD) and Predicted Mean Votes (PMV) recordings. The investigations uncovered relatively high PPD - PMV recordings relating to the Bungalow type buildings while the compound houses attune to the comfort zone. The Actual Mean Votes (AMV) of residents suggests the two building typologies are all rated comfortable however; the compound houses are rated above the bungalow type houses.

1. Introduction

Global climate change has heightened awareness on the need to minimize the use of CO_2 emitting energy sources. The need therefore for the usage of passive tactics for the mitigation interior environments as a way of improving comfort conditions is pertinent [1]. The Guinea Savannah climate is noted for high daily mean temperatures leading

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to building interiors heating up to uncomfortable levels due to solar penetration. Compound houses as one of the most common typologies of domestic dwellings in Tamale are not spared of this menace. The use of unsuitable building materials coupled with design and fenestration issues render these houses thermally uncomfortable. Bioclimatic design strategies have been studied and practiced widely [2]. Amongst these strategies are the inclusion of courtyards within houses so as to introduce outdoor conditions into the core of these structures to optimize climatic conditions. Incident radiation from the sun hitting walls and planes in the courtyard will influence the effective heat capacity of these structures particularly in spaces that adjoin the courtyard. Factors such as weather conditions, seasons and the courtyard's disposition of buildings with internal courtyards have been widely studied. Examples can be found in [3,4]. However most studies usually evaluate different building typologies other than the compound house.

It is the stated intention of this work to examine the effects and efficacy of internal courtyards on the effective heat capacity of compound houses in Tamale, Ghana. The research will also contribute significantly to the effective utilization of internal courtyards in building design to ensure thermal comfort with minimal energy consumption and hence reduced CO_2 emissions mostly from the fossil fuel sources used to power these buildings.

2. The Area of Study

The Tamale Metropolitan Area is Ghana denotes the geographical and administrative boundaries of the provincial capital of the Northern region. It has a total population of 371,351 and 922 km^2 land area [5].

The region comprises of twenty seven (27) districts. Situated centrally in the region, the Tamale metropolis shares borders with to the south-west by Central Gonja, to the east by Mion, to the south by East Gonja and to the west and north by the Sagnarigu districts. The Metropolis has total estimated land size of 64,690,180 sqkm. The area strides longitudes 0º 36 and 0º 57 west and latitude 9º16 and 9º 34 north [6].

Amidst an equatorial climate, the Metropolis stands at 195m above sea level. There are two seasons in a year: the rainy (from April to September) and the dry seasons (from October to March). In the course of the latter season, (Mid November to end of January) dry winds from the Sahara blow across the region. In Tamale, the average annual temperature is 27.9 °C / 82.2 °F. Annual precipitation records about 1111 mm / 43.7 inches. The month of September usually records the most the humidity, while the least humid month is December. A recorded percentage of 47.0% represents the mean annual relative humidity. The windiest portions of the year spans eight months, from December to August, with speeds of averaging higher than 6.1 miles per hour [7].

The Tamale Metropolis has an aggregate housing stock of 19,387. This takes up 7.5% of the whole count of dwellings in the region while 35,408 is the total sum of households. On the average a 6.3 household size pertains in the metropolis, this is below the 7.8 recorded for the region. The compound house constitutes the highest portion of residential buildings in the area at 80.6% of the total. The next is the detached house type which stands at 7.5% followed by semi-detached houses at 3.4%. Traditional huts comprising a number of small units made into a compound stands at 4.3% while Apartments or Flats comprise 2.1%. Kith and kin own approximately 55% of residential dwellings in the area. This individual proprietorship of houses recorded at 57.1% is greater in houses with male heads compared to 47.1% houses headed by females. The least value of 2.9% is owned by Government and Public institutions [5].

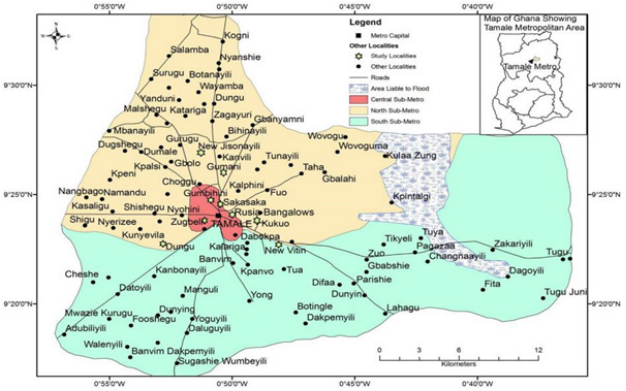


Figure 1. Delineation of the Tamale Metropolis.

Source: [8]

3. Statement of Problem

Recently, majority of buildings in Tamale and Ghana in general have increasingly adopted the use of glass for openings such as doors and windows. This exposes the facades to the high day time temperatures contributing to uncomfortable ambient conditions inside the interiors. With the purpose to reduce the undesirable effects of this vulnerability, builders and users of facilities have resorted to the application of mostly mechanical ventilation and air conditioning systems. The attendant problems such as high energy consumption and greater emission of Carbon dioxide (CO_2) from mostly fossil fuel sources. It is therefore imperative to engage alternative means

including passive design to ameliorate this situation.

4. Purpose of Study

The purpose of this study includes:

•Appraisal of the internal and external thermal comfort conditions of some chosen compound and bungalow type residential dwellings;

•To analogize the Actual Mean Votes (AMV) with the Predicted Mean Votes (PMV) among occupants of these chosen buildings.

5. Conceptual Framework and Literature Review

Energy efficiency is increasingly gaining priority as energy consumption from fossil fuel sources has become a serious concern [9]. Domestic buildings in the Tamale metropolitan area will record rising energy consumption as a consequence rising population and income. Consequently, this has generated increased momentum with regards to uncovering potent approaches and consciousness to low energy buildings. Generally, the use of artificial lighting in buildings is deemed to be a major source of consumption of total energy production as it leads to higher heating and cooling loads of buildings [10]. It is reckoned that artificial lighting takes up between 25% - 40% of total energy usage [11].

More research findings reveal that immense gains can be made in enhancing building energy efficiency by the addition of internal courtyards into buildings. They act not only as daylight- enhancers but also bring in ample ventilation into interior spaces consequently minimizing the need for HVAC systems. As a result of this, all dimensions of the courtyards in buildings (i.e. distribution, position, form and size, altitude, shading devices etc.) need to be thoroughly deliberated at the initial design stage. Inadequate design could result in difficulties in the control of ambient conditions such as temperature and glare.

Over the last decades, achievements have been made in creating conducive environments for all kinds of activities. The main ones being the creation of environment to sustain ambient comfort conditions for users of buildings because they directly impact health, productivity and morale.

Additionally, [9] posits that thermal comfort is realized when a thermal balance is attained: a condition whereby heat storage does not occur in the substance. Though it can be attained over a wide spectrum of parameters, it is also attributed to conditions to which substances easily adapt to. [12] describes thermal comfort as the state of the mind that expresses satisfaction with the surrounding environment. Criterion like the ASHRAE Standard 55 and ISO Standard 7730, [13] has formed the foundation for evaluation of thermal comfort conditions by a greater proportion of experts.

However, different climatic zones, present different comfort conditions for human beings: a situation which may differ vastly from this set global criterion.

Four key elements including relative humidity, mean radiant temperature, dry bulb temperature and air velocity exert immense influence on the determination of thermal comfort conditions. There are also two additional personal elements; (insulation/ clothing index and exercise).

The stipulations of the criterion of thermal comfort by ISO 7730 are among the pioneering works that have received worldwide attention [14]. This forms the basis of Fanger's investigations using Danish students in climate controlled chamber experiments. This later gave rise to the development PMV model.

The hot and dry guinea savannah region of Tamale can be classified into the most challenging climate to mould through design. This is as a result of high outdoor temperatures and fluctuating humidity conditions. Indoor temperatures can rise very high above the ASHRAE comfort ceiling of 26˚C in summer. The desired result for comfort is that which enables up to 90% of residents/users feel ambient comfort for most part of the year [15].

The Fanger-based criterion, which is otherwise referred to as the heat-balance method, was initiated through investigations in climate controlled enclosures later resulting into the PPD – PMV prototype. It was first mooted by Fanger in the 1970s.Working together with 1296 student participants' draped in systemized clothing. These participants were made to go through regulated tasks comparable to metabolic rates of around 1.2 Mets or 70 W/m^2.

This criterion (Predicted Mean Vote PMV) has since been used as part of global standards in the prediction of comfort conditions of residents/users of buildings. It is said to be extensively applied by architectural scientist and researchers to assess indoor comfort conditions [25]. The PMV criterion employs the four comfort conditions of relative humidity (%), air velocity (m/s), mean radiant temperature (˚C), air temperature (˚C). Another pair of personal variables i.e. clothing index (Clo) and metabolic rate (Met) are also applied. The computation of these parameters forms an index that is useful in the prediction of comfort conditions in spaces. This index furnishes scores that align with the ASHRAE 'thermal sensation scale'. It constitutes the average thermal sensation experienced by users [16].

Table 1 shows the seven point 'ASHRAE thermal sensation scale'. On the whole, field studies in comfort conditions [16] have reckoned the PMV template does inadequately forecast real thermal sensation of occupants from time to time. Errors in mensuration and circumstantial suppositions mostly account for the variance.

Table 1. ASHRAE Thermal sensation scale

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Source: [12]

Thermal comfort researchers have cited factors that can lead to skewed results of the PMV model. These include, mensuration of the physical variables with dependable equipment, clothing indices, exercise, contrasts in individuals, variations in buildings, outdoor conditions, adjustments relating to behavior and psychology adaptation all account for this. The PMV template is considered by most studies as the preferred means of prediction in buildings ventilated by mechanical means [10]. Inconsistences have also been noted between thermal feelings recorded from occupants and the PMV template in naturally ventilated buildings, [28]. Research indicates that thermal sensation of residents or users tends to be either under or over estimated by the PMV. The major criterion of design for thermal comfort is often considered to be air temperature; hence it is essential for occupants' efficacy and welfare [18].

Consequences related to ambient conditions on sensations of thermal comfort have been widely investigated by. Solar ingress by way of external windows makes up to 25% - 28% of the total solar heat gain. The relative positioning and plan formation of buildings have an effect on their ventilation and the radiation bearing potential [19]. To optimize heat gain from the sun and ventilation conditions, buildings need to be positioned such that their elongated ends face the prevailing wind direction to enable them catch these winds, while the short ends are towards incident solar ingress. The desirable effects shading mechanisms on comfort conditions have also been noted by [20].

[24] in Germany have investigated comfort conditions and the satisfaction of users of low energy consumption offices. Their findings indicate that "just right" and "slightly warm" votes falls in line with the baseline temperature of above 27˚C. Also, it was observed that PMV is quite extensive but varied marginally on the sensation scale, contingent on factors such as the nature of the subjective responses of ("slightly warm" "very warm" or "just right"). Other related research undertaken by [20] during the summer season in the United Kingdom observed a 23.9˚C average temperature with 21.6˚C to 26˚C span. −0.25 average PMV recording consistent with a span of −1.6 to 0.5. [11]. Findings from investigations of domestic buildings in London also established temperatures averaging around 23.8˚C.

On the contrary, not enough thermal comfort research has been carried out in Ghana [22-24].

The need therefore to build incrementally on literature in this subject area is pertinent. The impact of thermal comfort and indoor ambient conditions exert significant impact on morale, productiveness and well-being. Consequently the objective of this research to examine the extent of thermal comfort in residential buildings (i.e. compound houses and bungalow type houses) using the PMV-PPD model. In the end, researchers and practitioners in the industry will benefit from the findings and best practices found by the study. This can also help to improve thermal comfort conditions in the buildings under study.

6. Research Methodology

Thermal comfort of residential buildings (i.e. compound houses and bungalow type house) was investigated through quantitative research coupled with questionnaires for the residents of these building. The thermal comfort index (PMV), the foundation of this research is widely accepted to be useable in a particular environmental setting for reasons as follows:

Fanger's investigation is founded on a broad spectrum of climatic parameters, such as a recording of greater than 30˚C for air temperature and a value of up to 70% for relative humidity. PMV values ranging from recordings of −3 noted as cold to +3 noted as hot are acceptable as a moderate thermal environment.

Ten buildings (five compound houses and five bungalow type houses as shown in Table 2) at different locations within the Tamale Metropolis were selected for studies. The selected buildings represent a crossection of recent residential design and building trends within the metropolis.

There were 150 occupants selected from all 10 buildings to participate in the study. All the participants were residents in these buildings. Most of them had lived in the selected houses between time periods ranging from six months to fifteen years. The respondents were made up of 73 females and 77males. The age demographics of respondents were as follows: forty-six (46) persons were in the 25 – 35 age bracket, thirty-nine (39) were below 25 years, forty (40) persons between the ages 36 - 45 years

and twenty-five (25) persons over the age of forty-five (45).

Experimental Design

Field investigations were undertaken from the 30th March, 2018 to 28th February, 2019, spanning both the rainy and the dry seasons in the Tamale metropolis.

The respondents' subjective data were gathered through thermal comfort questionnaires. Objective data on the other hand were gathered through HOBO data loggers placed at various points in the living and bedrooms of the buildings to measure ambient conditions. Parameters such as relative humidity levels and indoor temperature were recorded at 30 minute cycles. A sum total of 486,452 datum points was collected and used in the research. The seven stage thermal sensation ranking by ASHRAE was employed to find out respondents' thermal sensation otherwise referred to as Actual Mean Votes (AMV) from them. Subsequently their Actual Mean Votes AMVs are analogized with their Predicted Mean Votes (PMV). Questionnaires also considered how occupants usually dressed around the house (clothing index). Added to this is a thermal insulation of furniture index of (0.1) to the clothing index of each participant.

Lastly, a rate of metabolism of up to 1.2 mets stated in [13] was adopted for occupants for living and bedroom activities.

Onset hobo sensors were employed to record Relative Humidity (R.H) and air temperature (T). The hot wire anemometer was engaged in the measurement of air velocity (A.V). These ambient parameters were recorded from about 1.1 m above the floor level. This aligns with the anthropometric dimension of an occupant in a sitting position. Reliability limits of these instruments used are illustrated in (Table 3).

Table 3. Reliability of measuring instrument

Comfort parameter	Range of measurement	Reliability limit
Relative Humidity (R.H)	From 5% to 95%	± 3%
Air Velocity (AV)	From 0.1 to 25.0 m/s	±5% ±0.1 m/s
Air Temperature (T)	From -20˚C to 70˚C	± 0.4˚C

The Predicted Percentage of Dissatisfied occupants (PPD) as well as the Predicted Mean Vote (PMV) was computed through the (PMV CALC V2) operating system. The processes involved the capture of aggregate values of items including, relative humidity, air velocity and temperatures, clothing index and metabolic rate recordings were loaded onto the operating system.

Subsequently, the outcomes were analyzed and presented in tabular form.

7. Data Analysis

The use of greenline operating system was employed to set up and download data from the instruments used to collect data from the various spaces. Sorting and export of the readings to Microsoft Excel document format constituted the next step. Data files were again sorted and constructed into tables showing month on month readings. Formulae sheets were effectuated to provide mean hourly recordings. The periods of high occupancy in the various houses i.e. from 5:0 am to 9:00 am and from 3:00pm

Table 2. Summary of selected buildings.

Building code	Floor area (m^2)	Location	Orientation	Spaces monitored	Thermal controls	Window type	Usage
CH1	420	Kanvili	North-South	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
CH2	435	Agric. Ridge	North-South	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
CH3	506	Kalpohin	East-West	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
CH4	412	Changli	East- West	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
CH5	409	Nyohini	South-East	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
B1	104	Kanvili	North-South	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
B2	138	Agric Ridge	North-South	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
B3	113	Kalpohin	East-West	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
B4	146	Changli	East-West	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping
B5	129	Nyohini	South-East	Bedrooms, Living rooms	Internal, Manually controlled	Timber framed louvred	Living, dining, sleeping

to 10pm. Descriptive statistics were then employed to analyze generated values.

8. Discussion

The research results are as presented below. They provide insights into the thermal comfort levels of the buildings under study.

Mean outdoor temperature recorded the lowest reading of 25.6˚C (in November) matching with 28% Relative Humidity during the research period. The highest temperature of 36˚C was recorded in March with 56% Relative Humidity. Relative Humidity however peaked in September with a recording up to 70% while the month of December recorded the least value of up to18%. These recordings comprehensively cater for the two main climatic seasons in Tamale, Ghana. The Predicted Percentage of Dissatisfied Persons (PPD) as well as the Predicted Mean Votes (PMV) of residents and the associated is illustrated. The Actual Mean Votes (AMV) of participants was then decided.

The results show that Relative humidity readings average in the compound houses averaged around 58%, 65% and 67% compared to 69%, 73% and 75% in the bungalow type houses.

The subjective feeling of relative humidity is also analyzed. The respondents generally expressed satisfaction with the magnitude of humidity in the houses perhaps as a result of the known fact humidity levels within 6% - 90% show no significant influence on comfort conditions.

As Table 4 illustrates, the compound houses show average air temperatures of (23.4^{o}C- 25.6 ^{o}C) lower than that for the bungalow type houses (27 ^{o}C -30 ^{o}C). The recordings for the former is in tandem with ASHRAE's allowable temperature limits of between 23˚C - 26˚C [12], the latter has higher reading.

However, many studies have stated that the tropics exhibit high comfort temperatures while humans also have the capacity to adapt to different climatic conditions [25]. It has also been reported that a 23.6˚C - 28.6˚C comfort spectrum in Malaysia (an example of Tropical climate) for all typologies of buildings [23].

Table 4 again shows that air velocity for Bungalow type houses falls between 0.2 – 0.48 m/s and 0.9 -1.32 for the compound house type. The average of 0.65 m/s for bungalow type and 1.0m/s for compound houses illustrates better air flow in the compound houses due to the presence of internal courtyards.

In the bungalow type houses, average Predicted Mean Votes recorded up to 1.65 (noted to be warm) which carries 55% Predicted Percentage of Dissatisfied Persons. Meanwhile, the indoor temperature ranged from 27 - 30˚C. These readings are at variance with other studies. Readings of 21.6˚C - 26˚C thus averaging up to 23.9˚C for indoor temperature were recorded in that investigation. The Predicted Mean Votes recorded (−0.25) rendering the bungalow houses hotter (PMV of 1.65).

Conversely, compound houses recorded an average PMV of 0.7 (closer to "just right") which matched up to 39% PPD. At the same time, recorded the indoor temperature were between 2 3.4-25 ˚C.

Factors such as form and orientation, courtyards to enhance cross ventilation, proportions of eaves in the direction of the prevailing winds, lateral walls etc. need to be into account especially for buildings that rely on natural ventilation [23]. Fitting of ceiling and/or wall fans within the buildings can also enable up to a 2˚C

Table 4. Summary of indoor measurements.

Comfort parameter	Unit	CH1	CH2	CH3	CH4	CH5	B1	B2	B3	B4	B5
Average Air temperature (min-max)	˚C	23.9 (24to27.5)	25.6 (23to26.8)	23.4 (23to28)	24 (23.7-28)	23.8 (24to28.6)	27 (24to28.6)	29 (24to30)	30 (26 to32)	29 (25to31)	29.7 (26to32)
Average Relative humidity (min-max)	%	58 (56 to 60)	63 (57 to 66)	59 (58 to 64)	65 (60 to 66)	66 (58 to 67)	67 (58 to 70)	69 (65 to 70)	61(59 to 68)	69 (58 to 70)	68 (64 to 72)
Average Air velocity (min-max)	m/s	1.2 (0.5 to 1.8)	0.9 (0.7 to 1.8)	1.0 (0.85 to 1.9)	1.15 (0.5 to 1.9)	1.32 (0.75 to 2.0)	0.25 (0.2 to 0.75)	0.3 (0.2 to 0.7)	0.2 (0.2 to 0.80)	0.4 (0.3 to 0.85)	0.48 (0.4 to 0.9)
Clothing index	clo	T-shirt, shorts sports clothing and light trousers. Clothing insulation index used (0.57clo).									
Average PMV (min-max	-	0.5(-0.3 to 0.85)	0.65 (0.5 to 1.0)	0.89 (-0.5 to 0.9)	0.8 (0.7 to 1.2)	0.6 (1.0 to 1.9)	1.75 (-0.5 to 1.9)	1.5 (1.0 to 1.8)	1.65 (0.3to1.9)	1.7 (-0.5 to 1.8)	1.65 (-0.5to1.8)
Average PPD (min-max	%	38 (25to45)	44 (55to70)	40 (35-50)	35 (30to50)	39 (45to65)	55 (60to75)	58(50to65)	57(24to40)	49 (40to65)	58 (50to70)
Average AMV(min-max)		-0.85 (-2.5to3)	-0.6 (to2-3)	0.45 (-3-2)	0.65 (-2to1.5)	-0.5 (-3to2.5)	-0.7 (-3to2)	-1.2 (-2to0)	-1.5 (-3to0)	-0.5 (-3to2)	-1.35 (-3to 0)

temperature reduction [23].

The recorded average indoor temperature of the compound houses could also be associated with orientation of the buildings (north-south), wide overhangs, courtyards and in some cases trees as shading.

The slightly warm PMV for the bungalows, is as a result of orientation (in some cases east-west) and the lack of shading, no internal courtyards, some amount of glazing in the fenestration.

PMV computation for the two building types as shown in Table 4 reveals that residents of compound houses reported more desirable comfort conditions. Readings align with the major categories classification of the thermal sensation scale.

Inconsistencies between the PMV and the average AMV in both compound and bungalow type also exist. (Table 4).

It is pertinent to state also that over-prediction of PMV was recorded in the indoor thermal comfort in the both building typologies by around 1.5 scale units. These results are consistent with the findings of other studies [25]. The study noted a divergence of 1.3units in Predicted Mean Votes and Actual Mean Votes. Excesses in the forecast of PMV have also been found by other researchers in related studies [26].

Major causes that could be assigned to the over-prediction of PMV in the present research can be outlined as:

Respondents had the flexibility of use of appliances, building elements and nature itself. These include the use operable louvered windows, standing, wall and ceiling fans, trees and shrubs for shading.

Additionally, the respondents in the buildings mostly go to work during the mornings when temperatures are known to be tolerable Majority of respondents about (78%) remaining at home in the afternoons would usually sit outside in the shade when recorded temperatures are very high.

The other case for the over prediction could also be attributed to respondents acclimatization to the ambient temperature and humidity recordings hence the feedback.

Significant differences inside the internal spaces could have also led to the high value of the PMV compared to Fanger's situation during the climate controlled enclosure investigations. These include use of gadgets for cooking, ironing etc. Individual configuration of spaces and human activity within also plays a critical role. Some respondents who are at locations astride openings may report more comfortable conditions especially in the early hours of the day when openings are not shut. (58.7%) meanwhile respondents located deeper within the spaces reported less comfortable (15.4%).

9. Conclusions

Data analysis and results from the assessment of comfort parameters in compound houses as well as bungalow type buildings presented by this investigation. The purpose of this endeavor was to evaluate thermal comfort levels of in these building typologies juxtaposed against the ASHRAE 55 and ISO 7730 criterion. Fanger's PMV-PPD model was harnessed to investigate ambient comfort levels in the compound and bungalow type houses.

The synthesis of results and further deliberations explicitly shows that the Predicted Percentage of Dissatisfied Persons (PPD) as well as the Predicted Mean Vote framework ably forecasts ambient comfort parameters in these building typologies. Therefore, ambient comfort conditions recorded in these buildings identify properly with the ASHRAE and ISO standards. However some over-prediction issues acknowledged earlier also exist. The compound houses average temperature record of 24.5˚C and 27.5 ˚C bungalow type houses (though higher) conforms to the ASHRAE's 23˚C - 26˚C summer tolerable temperature.

Furthermore, the average of satisfied users/occupants for compound houses of around 88.7% can also be said to align favorably with the International Standards Organization 7730's limits 75%. It is also 90% close to the American Society of Heating Refrigeration and Air conditioning Engineers' recommendation rate of satisfied respondents. This is noted to be at variance with conditions of the bungalow type of 59.8%.

In conclusion, it is imperative to state the limitations of this study; errors in mensuration such as measurement of physical variables with dependable equipment and circumstantial suppositions e.g. clothing indices, exercise, individual idiosyncrasies, variations in buildings, outdoor conditions, adjustments relating to behavior and psychological adaptation could all contribute to some margin of error.

10. Recommendations

It is recommended that adaptive measures should be employed to improve ambient thermal comfort in these buildings. Some of the recommended measures include the incorporation of internal courtyards, shading devices (both natural e.g. trees, shrubs etc. and built forms), orientation to catch prevailing winds and reduce solar ingress and increase size of windows.

Lastly, more research is recommended to establish

the dependability of the PMV-PPD in the prediction of ambient thermal sensation within the building typologies used in this study. This will facilitate the development of best practices consequently resulting to efficient design, construction and use of these buildings.

References

[1] Givoni, B., 1994. Passive and Low Energy Cooling of Buildings. 1st Edn, Van Nostrand Reinhold, New York, ISBN: 0471284734, pp: 4.

[2] Budaiwi, I.M., 2006. An approach to investigate and remedy thermal-comfort problems in buildings. Build. Environ, 42: 21 24-2131.

[3] Al-Hemiddi, N.A. and K.A. Megren Al-Saud, 2001. The effect of a ventilated interior courtyard on the thermal performance of a house in a hot-arid region. Renewable Energy, 24: 581-595.

[4] Muhaisen, A.S. and M.B. Gadi, 2006. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. Build. Environ. 41: 245-253.

[5] GSS. (2012). 2010 population and housing census: Summary report of final results. Accra: Ghana Statistical Service.

[6] Abankwa, V., Grimard, A., Sommer, K., & Kuria, F. (2009). Ghana: Tamale city profile. Nairobi: Regional Technical Cooperation Division, UN-Habitat.

[7] Ghana Meteorological Service, 2018.

[8] Ibrahim Yakubu*, Millicent Awialie Akaateba, Bernard A.A. Akanbang,(2014) A study of housing conditions and characteristics in the Tamale Metropolitan Area, Ghana, Habitat International Vol. 44 pp 394-402.

[9] Nicol, F.G. (2001) Characterising Occupant Behaviour in Buildings: Towards a Stochastic Model of Occupant Use of Windows, Lights, Blinds, Heaters and Fans. Proceedings of 7th International IBPSA Conference, Rio de Janeiro, 13-15 August 2001, 1073-1078.

[10] Brager, G.S. and De Dear, R.J. (1998) Thermal Adaptation in the Built Environment: A Literature Review. Energy and Buildings, 27, 83-96.

[11] Oseland, N.A. (1995) Predicted and Reported Thermal Sensation in Climate Chambers, Offices and Homes. Energy and Buildings, 23, 105-115. DOI: http://dx.doi.org/10.1016/0378-7788(95)00934-5.

[12] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (2004) Standard 55-2004 & Standard 55-1992, Thermal Environmental Conditions for Human Occupancy. ASHRAE, Atlanta.

[13] ISO 7730 (2005) Moderate Thermal Environments Determination of the PMV and PPD Indices and Specifications for Thermal Comfort. 2nd Edition, International Organization for Standardization, Geneva.

[14] Szokolay, S. (2004) Introduction to Architectural Science: The Basis of Sustainable Design. Architectural Press, Oxford, 17.

[15] Hyde, R. and Sabarinah, S.A. (2008) Bioclimatic Housing, Innovative Designs for Warm Climates. Earthscan, UK & USA.

[16] Humphreys, M.A. and Nicol, J.F. (2002) The Validity of ISO-PMV for Predicting Comfort Votes in Everyday Thermal Environments. Energy and Buildings, 34, 667-684. DOI: http://dx.doi.org/10.1016/S0378-7788(02)00018-X.

[17] Fanger, P.O. (1970) Thermal Comfort. Danish Technical Press. Copenhagen.

[18] de Dear, R.J. and Brager, G.S. (2002) Thermal Comfort in Naturally Ventilated Buildings: Revision to ASHRAE Standard 55. Energy and Buildings, 34, 549-561. DOI: http://dx.doi.org/10.1016/S0378-7788(02)00005-1

[19] Beizaee, A., Firth, S.K., Vadodaria, K. and Loveday, D. (2012) Assessing the Ability of PMV Model in Predicting Thermal Sensation in Naturally Ventilated Buildings in UK. 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World, Windsor, 12-15 April 2012, Network for Comfort and Energy Use in Buildings, London. http://nceub.org.uk.

[20] Han, J., Zhang, G., Zhang, Q., Zhang, J., Liu, J., Tian, L., Zheng, C., Hao, J., Lin, J., Liu, Y. and Moschandreas, D.J. (2007) Field study on Occupants' Thermal Comfort and Residential Thermal Environment in a Hot-Humid Climate of China. Building and Environment, 42, 4043-4050. DOI: http://dx.doi.org/10.1016/j.buildenv.2006.06.028.

[21] Heidari, S. and Sharples, S. (2002) A Comparative Analysis of Short-Term and Long-Term Thermal Comfort Surveys in Iran. Energy and Buildings, 34, 607-614. DOI: http://dx.doi.org/10.1016/S0378-7788(02)00011-7.

[22] Barbara Simons, Christian Koranteng, Emmanuel Adinyira and Joshua Ayarkwa, (2014) An Assessment of Thermal Comfort in Multi Storey Office Buildings in Ghana, Journal of Building Construction and Planning Research, 2014, 2, 30-38.

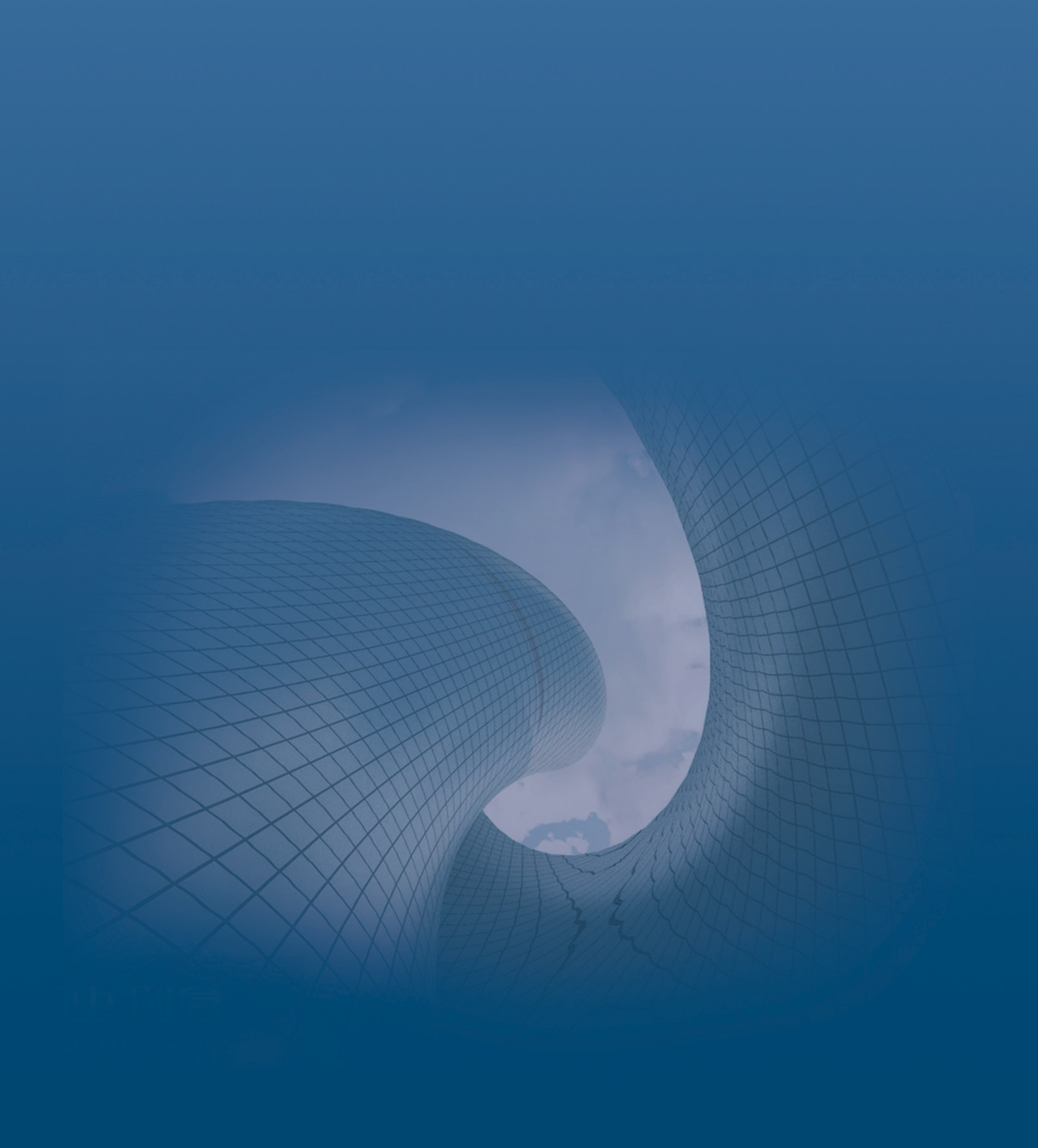
[23] Koranteng, C. and Abaitey, E.G. (2010) The Effects of Form and Orientation on Energy Performance of Residential Buildings in Ghana, Journal of Science and Technology, 30, 71-81.

[24] Koranteng, C. and Mahdavi, A. (2010) An Enquiry

into the Thermal Performance of Five Office Buildings in Ghana. 10th Revha World Congress on Sustainable Energy Use in Buildings (CLIMA 2010), Antalya, 9-12 May 2010.

[25] Doherty, T.J. and Arens, E. (1988) Evaluation of the Physiological Bases of Thermal Comfort Models. *ASHRAE Transactions*, 94, 1371-1385.

[26] Morgan, C.A., De Dear, R. and Brager, G. (2002) Climate, Clothing and Adaptation in the Built Environment. In: Levin, H., Ed., Indoor Air 2002: The 9th International Conference on Indoor Air Quality and Climate, Monterey, 30 June-5 July 2002, 98-103.



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