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Evaluating the Impact of Material Selections, Mixing Techniques, and On-site Practices on Performance of Concrete Mixtures

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Abstract

This paper aims to evaluate the influence of sand quality, water-to-cement ratio, binder properties, mix design methods, and mixing techniques on the fresh and hardened properties of concrete. The physicochemical characteristics of coarse aggregates, sands, and binders were analyzed. The experimental results show that the binders and coarse aggregates met standard specifications. However, none of the sands meet construction standards. Corrections were necessary for the dune sands to meet construction standards in terms of grain size distribution and fineness modulus. The results also show that the concretes formulated using the Dreux-Gorisse method exhibited higher quality than the locally formulated concretes. Furthermore, it was found that hand mixing resulted in inadequate mixing, material wastage, lower strength, and increased porosity, whereas machine mixing produced concretes with a more homogeneous microstructure, uniform particle distribution, lower porosity, and higher strength. The batch variability and compressive strength of the hand-mixed concretes were also found to be influenced by the expertise level of the batch mixer and the number of successive hand batches. It was also found that both the soluble silica and the inert methods are reliable for determining binder content in machine-mixed concrete. However, the soluble silica method occasionally exhibited significant variations in hand-mixed concrete compared to the inert method. A combined approach utilizing the average of both methods enhances the overall reliability of the binder content values. Observations on construction sites revealed widespread deviations from recommended guidelines. Issues such as lack of material inspection, proper stockpiling, ingredient contamination, and inadequate batch mixing contributed to variations in concrete workability, porosity, and compressive strength.

Keywords: Sand Quality; Dreux-Gorisse Method; Corrected Sand; Hand Mixing; Machine Mixing; Construction Site.

1. Introduction

Concrete is widely used in infrastructure projects globally due to its affordability and simple technology. Typically, concrete mixtures consist primarily of coarse aggregates (crushed stone or gravel), fine aggregates (mostly sand), cementitious materials (serving as a binder), water, and occasionally additives and admixtures. The fresh and hardened properties of concrete rely on the characteristics and volume fractions of these primary components, along with the

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water-to-cementitious materials (w/cm) ratio. An unusual condition that exists in any one of these components or that might arise from the combination of components would tend to alter the behavior of the concrete [1]. Weight-wise, aggregates (i.e., sand along with crushed stone or gravel) constitute around 50 to 80% of the total volume of concrete and between 70 and 85% of its mass, depending on the mixture proportion [2–5]. Consequently, their characteristics, including gradation, fineness modulus, maximum size, cleanliness, shape, and texture, significantly influence the properties and behavior of concrete [2, 3, 5, 6].

In terms of aggregate gradation, there is agreement that uniformly sized aggregate particles might not achieve proper compaction. Conversely, well-graded aggregates composed of various particle sizes result in smaller particles filling voids between larger ones during compaction. As a result, a concrete made with well-graded aggregates is more compact and possesses fewer voids, which greatly contribute to the overall quality of the concrete [5–7]. The particle size distribution of the fine aggregate also plays a crucial role in the workability, segregation, and pumpability of fresh concrete [7]. Similarly, the workability of concrete can vary with the shape, texture, and quantity of flat and elongated particles of coarse aggregates [2, 5, 8]. Furthermore, the nominal maximum size of aggregate is directly proportional to its specific surface area, which, in turn, affects the amount of mixing water needed to achieve a certain level of workability [5, 8]. Thus, as the maximum aggregate size increases, the required mixing water decreases. Reports in the literature also suggest that fine aggregates containing organic impurities can interfere with the hydration process, thereby potentially compromising strength development [7].

Thus, the quality of both the sand and coarse aggregate is essential in assessing the performance of structural concrete. Nevertheless, many local contractors in various parts of Africa often use readily available sand and coarse aggregate without considering their potential impact on the performance of the concrete [4, 7, 9–11]. Moreover, many of these contractors often lack the resources or capacity to conduct quality control on these materials before their use on site. Consequently, the fine aggregate (sand) often employed for concrete production on most construction sites may not be properly graded and could contain excessive fines (such as silt and clay), along with organic impurities that can lead to a reduction in strength [7]. For example, in a study by Olonade et al. [7], sands sourced from five supply points in Osun State, Nigeria, were investigated for suitability in structural concrete. Their findings revealed that only one sand (Sand E) met structural application criteria, while another (Sand A) was deemed suitable only for non-structural use.

In practice, over 80% of the concrete mixes in Morocco incorporate dune sand for construction projects, owing to its abundance, affordability, and scarcity of natural sand with satisfactory quality. Concrete made with 100% dune sand is mainly used by local contractors in the informal sector. While this aligns with the trend of using abundant materials in concrete for sustainable construction, the integrity of the dune sands for structural concrete has not been thoroughly investigated. Studies have, however, shown that using 100% dune sand in concrete reduces workability and strength [12, 13]. One reason put forward is their poor gradation, as dune sands typically consist of a considerable amount of very fine particles. Another reason given is their high salinity. Notwithstanding, dune sand is recommended as a partial replacement for fine aggregate in structural concrete [12–15]. Al-Harthy et al. [12] observed a decrease in compressive strength with increasing dune sand replacement due to the increased fine grain surface area. However, conflicting results can be found in the literature regarding the optimum replacement ratio for satisfactory strength. Bawab et al. [16] reported an optimum replacement ratio of around 20%, while Ahmed et al. [13] suggested a range of 30 to 40%. Al Harthy et al. [12] also recommended a higher limit of 60% for concrete. Per this viewpoint, further experimental studies are warranted in this regard.

The concrete batching process is equally vital in any concrete application [17], as proper batching of all materials is imperative for achieving a successful concrete mixture. Inadequate mixing can lead to notable inhomogeneities, poor packing of cement particles, and an increase in porosity, all of which can adversely affect the mechanical properties and durability of concrete structures [18]. Typically, concrete batching can be accomplished either through machine mixing (i.e., mechanical mixing) or the hand mixing process (i.e., manually with shovels and wheelbarrows). In Morocco, akin to several other developing nations [11], hand mixing is the predominant approach for batching concrete for most construction projects, including structural elements, notably within the informal sector. Indeed, Schmidt et al. [11] noted through site inspection that hand mixing is widespread on construction sites in Congo and is predominantly performed by laborers. Similarly, Tutu et al. [4] reported significant instances of hand mixing at construction sites in Ghana. The preference for hand mixing is often attributed to cost-saving measures and the volume of concrete often required for such construction projects [4].

Although the hand mixing method is commonly regarded as suitable only for non-structural works due to concerns such as slurry loss and non-uniform mixing [4, 19], many local contractors employ this method for both structural and non-structural works. Indeed, some contractors argue that hand mixing of concrete at the construction site can yield quality concrete that meets structural requirements when executed properly by experienced batchers. However, reliable material data on hand-mixed concrete (using shovels and wheelbarrows) is scarce, making it challenging to either support or challenge such claims. Despite numerous academic studies conducted in this area, most notably references [4, 11, 19–21], most of these studies have not thoroughly investigated the impact of the hand mixing method on the quality of the concrete mixtures, especially in real-world scenarios. For instance, references [4, 11] did not quantitatively evaluate the influence of the hand mixing process on the quality of the concrete batches.

A study by Olusola et al. [19] found that hand-mixed concretes typically fail to meet the requirements for structural concrete. Even more concerning, the hand mixing in this study was carried out in a laboratory setting, which may yield better results than those obtainable on typical African construction sites where water is added arbitrarily. The authors also followed a prescriptive (or recipe)-based method for the design of the mixtures, which significantly differs from the common practice of estimating mixture ingredients using a wheelbarrow or simply eyeballing them on most construction sites [20]. Similarly, Aguwa [21] conducted a study on the effect of hand mixing on concrete strength and concluded that a minimum of three turns is necessary to produce uniformly mixed concrete with satisfactory strength. However, like the study by Olusola et al. [19], the author followed a prescriptive-based method for the design of the mixtures and conducted hand mixing in a laboratory setting on a hard, clean, and non-porous galvanized iron tray, potentially resulting in higher strength than what would be observed on real-world construction sites. It is also widely recognized that poor construction practices, characterized by the use of unskilled labor and substandard construction materials, along with inadequate enforcement of established construction standards and regulations, significantly contribute to building collapses in developing countries [4, 9, 11]. The absence of routine inspections and testing protocols further compounds this issue, hindering the verification of compliance with specifications and drawings, if provided. Moreover, onsite stockpiling practices can also affect the properties of concrete. For instance, the exposure of aggregates to weather conditions can lead to substantial fluctuations in their moisture content, which in turn can result in variations in the water-to-cement ratios across different batches, ultimately influencing the properties of the concrete [4, 11]. Yet, no study has prospectively been conducted to systematically document the prevailing challenges linked to such practices and propose potential approaches to enhance or rectify some of these issues in Morocco.

The goal of the present study is, therefore, to conduct a comprehensive investigation into the factors influencing the quality and performance of concrete mixtures. Firstly, the study aims to evaluate the characteristics of coarse aggregates, dune sand, river sand, and binders from five regions of Morocco to determine their suitability for structural concrete. Secondly, the research seeks to determine the optimum replacement ratio of dune sand and crushed sand for structural concrete. Additionally, the study aims to evaluate the impact of machine mixing and hand mixing methods, including the expertise level of onsite hand mixers and prolonged hand mixing periods, on concrete quality. Furthermore, the research seeks to evaluate the influence of formulation methods, such as local practices and the Dreux-Gorisse method, as well as the water-to-cement (w/cm) ratio, on concrete quality. Moreover, the study seeks to use two concrete de-formulation approaches to estimate the in-place binder contents. Finally, the study aims to identify and address concrete quality issues at construction sites through onsite visits. The purpose is to conduct onsite visits to systematically document the prevailing challenges linked to aggregate sourcing, stockpiling, batching, as well as concrete mixture design, production, and construction practices. The overall findings of this research hold the potential to inform the development of more efficient and sustainable construction practices in Morocco, thereby contributing to the advancement of the construction industry in the region.

1.1. Scope and Framework of the Study

Five regions in Morocco, namely Tit Mellil, El Jadida, Settat, Marrakech, and Tamara, were chosen for this study, as depicted in Figure 1. These regions were selected due to the growing construction activities in these areas and their surroundings. Tit Mellil, located in the Casablanca region, experiences a Mediterranean climate with mild, relatively wet winters and moderately hot summers with no rainfall. The region has an average annual temperature of 18.0°C, with an annual rainfall of around 426.1 mm. El Jadida has a temperate Mediterranean climate with hot, dry summers, according to the Köppen-Geiger classification. The average yearly temperature is 17.8°C, with an average annual rainfall of 431.7 mm. Settat also has a temperate Mediterranean climate with hot, dry summers, an average yearly temperature of 17.4°C, and an average annual rainfall of 342.7 mm. Marrakech features a semi-arid Mediterranean climate, with an average annual temperature of 20°C and an average annual rainfall of 281 mm. Tamara, situated in the Rabat area, has a Mediterranean climate characterized by an annual precipitation of 527.9 mm with an average annual temperature of 17.2°C. The climatic data was sourced from a recent climate report on the state of the climate in Morocco [22]. The conceptual framework of the study is shown in Figure 2.

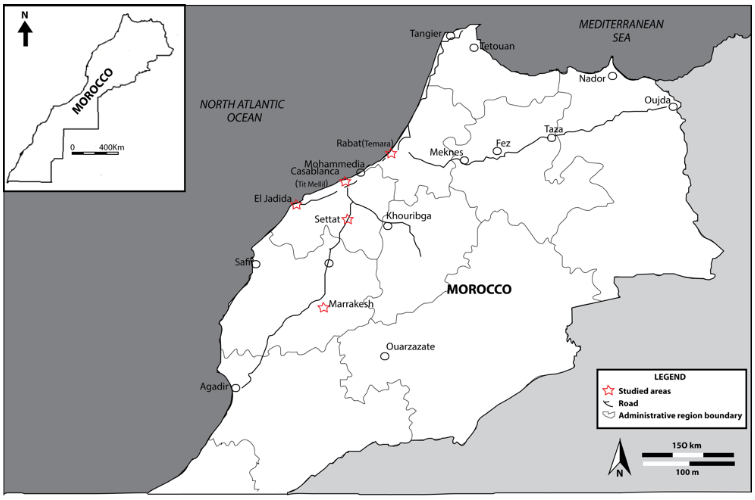


Figure 1. Selected studied areas

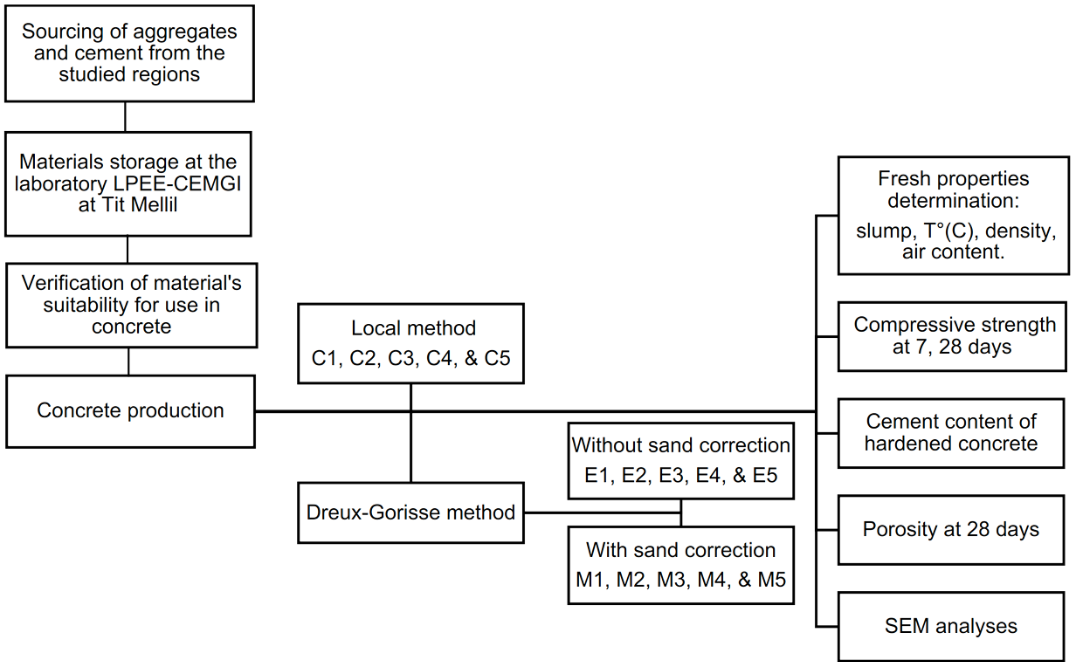


Figure 2. Experimental program

2. Material and Methods

2.1. Binder

The binders used in this study were locally produced Portland composite cement (PCC) of CPJ 45 type, supplied by CIMAT, CIMAR, Holcim, and Lafarge. These PCC binders consisted of clinker, limestone powder, and fly ash, albeit with varying compositions as shown in Table 1. The PCC binders met the specifications outlined in the Moroccan standard NM 10.1.004 [23]. The compound compositions and other properties of the binders were determined and are summarized in Table 2. In Table 1, PCC-1 from CIMAT was used as the binder type in Tit Mellil and El Jadida, whereas PCC-2 by Holcim, PCC-3 by CIMAR, and PCC-4 by Lafarge were utilized in Settat, Marrakech, and Temara, respectively.

Table 1. The variation of binding materials in the composite cement

Composite cements	Clinker (%)	Limestone (%)	Fly ash (%)
PCC-1	70.41	26.39	3.21
PCC-2	70.80	23.40	5.80
PCC-3	71.40	19.40	9.20
PCC-4	70.10	19.50	10.30

Table 2. Binder composition and fineness

Compound	PCC-1	PCC-2	PCC-3	PCC-4
Compounds, % by weight				
SiO_2	15.77	15.30	20.57	20.24
Al_2O_3	4.09	5.76	4.61	5.42
Fe_2O_3	2.2	2.38	2.53	3.78
CaO	57.33	58.18	54.25	56.14
MgO	1.5	1.05	2.65	0.85
SO_3	2.42	2.04	2.79	2.19
K_2O	0.94	0.48	0.65	1.11
Bogue compounds, % by weight				
C_3S	42.8	50.1	57.8	59.80
C_2S	25.0	18.9	15.0	13.07
C_3A	8.0	12.0	6.10	10.60
C_4AF	10.4	9.80	11.1	10.20

Other properties				
Chloride, %	0.0053	0.0140	0.0400	0.0014
Sulfate, %	2.60	1.74	2.41	1.06
Loss on ignition	14.21	15.49	11.28	10.51
Absolute density, kg/m^3	2940	2910	3000	2950
Blaine fineness, cm^2/g	3950	3680	4031	3520
Initial setting time (min)	235	220	160	255
Final setting time (min)	340	325	235	340
Compressive strength, (MPa)	37.1	35.7	39.8	40.4

2.2. Aggregates

Fine aggregate: The primary fine aggregates used were dune sand and river sand. Crushed limestone was also used, either as a partial substitute for dune sands or as a complete replacement for natural river sand. Before designing the concrete mixtures, the characteristics of the sands were evaluated. The maximum particle sizes were determined according to NM EN 933-1 [24], while the fineness modulus and the fine content (i.e., particles with diameters less than 80 µm.) were determined per EN 12620 [25]. The water absorption and density of the sands were determined per NM EN 1097-6 [26]. Additionally, the Methylene blue and sand equivalent content were assessed following EN 933-8 [27] and NM EN 933-9 [28], respectively. Furthermore, the chloride and sulfate contents were determined in accordance with the guidelines specified in NM EN 1744-1 [29, 30]. The particle size distributions of the sands were also determined using the sieving method outlined in NM EN 933-1 [24].

Correction of superfine sand: The fineness modulus and particle size distribution of the sands classified as very fine were modified to fulfill ASTM C33 [31] requirements. In this paper, the particle sizes of the sands were corrected using the Abrams rule [10, 32], which involved blending coarse sand with a high fineness modulus (FM_{CS}) and a fine sand with a fineness modulus (FM_{FS}), to achieve a targeted fineness modulus (FM_{OPT}) of 2.5, which is within the acceptable range of the ASTM and NM EN12620 criteria. The proportions of the two sands were determined as:

$$\text{Proportion of coarse sand in the mixture:} = (FM_{OPT} - FM_{FS})/(FM_{CS} - FM_{FS}) \quad (1)$$

$$\text{Proportion of fine sand in the mixture:} = (FM_{CS} - FM_{OPT})/(FM_{CS} - FM_{FS}) \quad (2)$$

***Coarse aggregate*:** The coarse aggregates used were crushed gravels. The characteristics of the gravels were also evaluated prior to designing the mixture. The maximum particle sizes were determined per NM EN 933-1 [24], while the fine content was determined per NM EN 12620 [25]. The water absorption and density of the sands were determined following NM EN 1097-6 [26]. Additionally, the flattening coefficient content and the Los Angeles coefficient were determined as per NM EN 933-3 [33] and NM EN 1097-2 [34], respectively. The chloride and sulfate contents were determined in accordance with NM EN 1744-1 [29, 30]. The particle size distributions of the sands were determined using the sieving method outlined in NM EN 933-1 [24].

2.3. Water

The water used for the mixing was portable water taken from the outflow of the Tit Mellil aqueduct system. The water had a pH of 7.46, dry extract of 456.00 mg/L, alkalis concentration of 118,09 mg/L, chloride concentration of 141.84 mg/L, sulfate concentration of 84.79 mg/L, sodium chloride (NaCl) of 233,74 mg/L, sodium sulfate (Na_2SO_4) of 125,42 mg/L, and sodium carbonate (Na_2CO_3) of 0.00 mg/L. Thus, the quality of the water used was in accordance with the requirements of the NM 10.1.353 standard [35].

2.4. Mixture Designs

The study investigated non-air-entrained concrete mixtures with a target compressive strength of 25 MPa tailored for the XCA2 exposure conditions as defined in Table 1 of NM 10.1.008 [36]. These conditions are equivalent to the XC3 (i.e., moderate humidity) and XC4 (i.e., cyclic wet and dry conditions) exposure conditions outlined in Table 2 of EN 206-1 [37]. Two concrete mixture design methods were used, namely the *local method*, which mimics the common practice on construction sites, and the *Dreux-Gorisse method*, a more elaborate scientific approach [32]. The compositions of the fifteen mixtures are detailed in Table 3. For the *local design method*, the mixtures (i.e., C1 to C5) were deliberately formulated to replicate local practice based on the quantities of ingredients used during preliminary hand mixing tests. Mixture C1 mimicked the mixture used in Tit Mellil, while Mixtures C2, C3, C4, and C5 mimicked those used in El Jadida, Settat, Marrakech, and Tamara, respectively. These mixtures served as the control mixtures. For each locally designed mixture, two Dreux-Gorisse mixtures were formulated, resulting in ten mixtures in total. Among these ten mixtures, five mixtures used the same *uncorrected sand* as in the locally designed mixtures (i.e., E1 to E5), while the remaining five used the *corrected sand* (i.e., M1 to M5). The Dreux-Gorisse mixtures were formulated to have a targeted minimum cementitious materials content of 310 kg/m^3 and a maximum total water-to-cementitious materials (w/cm) ratio of 0.60 as stipulated in NM 10.1.008 [36] for the exposure class XCA2 (i.e., XC3 and XC4 in the EN 206-1 standard [37]). No *mineral additives* and *chemical admixtures* were used to mimic local practices in the country.

Table 3. Codification and composition of the concrete mixtures tested - Machine mixing (unit: kg/m^3)

Materials / Property	Tit Mellil			El Jadida			Settat			Marrakech			Temara		
	C1	E1	M1	C2	E2	M2	C3	E3	M3	C4	E4	M4	C5	E5	M5
Binder	242	350	350	313	350	350	460	350	350	462	350	350	420	350	350
Dune sand	730	625	208	991	725	209	536	176	210	588	625	209	527	615	210
River sand	-	-	-	-	-	-	525	657	-	-	-	-	-	-	-
Corrected sand	-	-	615	-	-	620*	-	-	604	-	-	620	-	-	612
Coarse aggregate	1171	1210	1006	847	1102	996	475	961	976	892	1187	982	1076	1210	1002
Effective water	210	193	193	189	193	193	256	193		280	193	193	260	193	193
Total water	222	210	210	219	210	210	274	210	210	296	210	210	268	210	210
Effective w/cm [a]	0.87	0.55	0.55	0.61	0.55	0.55	0.56	0.55	0.55	0.61	0.55	0.55	0.62	0.55	0.55
Total w/cm [b]	0.92	0.59	0.60	0.70	0.60	0.60	0.60	0.60	0.60	0.64	0.60	0.60	0.64	0.60	0.60

[a] Excludes water absorbed by aggregates; [b] includes water absorbed by aggregates; * corrected sand from Settat

It should be mentioned that the mixture compositions presented in Table 4 were calculated by estimating the ingredients used during hand mixing. In this process, the mixture ingredients were estimated using a wheelbarrow, or in some cases, visually estimated by the batch mixers. To ensure accurate determination of the quantity of each material used, the total quantity of each ingredient was weighed and recorded prior to the arrival of the batchers. Thus, by weighing the remaining material post-batching, it became possible to calculate of the mixture proportions for the hand mixing process.

Table 4. Codification and composition of the concrete mixtures tested - Hand mixing (unit: kg/m^3)

Materials / Property	Tit Mellil			El Jadida			Settat			Marrakech			Temara		
	C1	E1	M1	C2	E2	M2	C3	E3	M3	C4	E4	M4	C5	E5	M5
Binder	250	359	360	323	360	361	469	361	360	473	360	361	428	360	361
Dune sand	728	615	209	980	716	210	526	175	210	575	618	210	517	607	210
River sand	-			-			516	641		-			-		
Corrected sand	-		605	-		608*	-		595	-		610	-		603
Coarse aggregate	1141	1189	987	825	1081	977	456	945	957	872	1165	966	1054	1188	983
Effective water [a]	219	202	200	199	201	201	264	202	200	289	201	200	269	201	200
Total water [b]	231	217.9	217	228	218.1	218	285	218.1	216	305	217.4	217	276	217.3	216
Effective w/cm [a]	0.876	0.562	0.556	0.615	0.557	0.555	0.563	0.560	0.556	0.612	0.560	0.555	0.627	0.558	0.556
Total w/cm [b]	0.925	0.607	0.603	0.705	0.606	0.602	0.607	0.605	0.602	0.645	0.604	0.602	0.645	0.603	0.600

[a] Excludes water absorbed by aggregates; [b] includes water absorbed by aggregates; * corrected sand from Settat.

2.5. Mixing

To comprehensively evaluate the impact of the mixing process on the performance of the mixtures, two batching methods. Firstly, the hand mixing approach with shovels and wheelbarrows was utilized to replicate on-site practices in Morocco and many African countries. Secondly, machine mixing with a laboratory pan mixer was employed.

2.5.1. Hand Mixing

Hand mixing involves manually blending concrete mixture ingredients without machinery (i.e., with shovels and wheelbarrows or head pan). The batch mixer begins by spreading the coarse aggregate, followed by the sand (Figure 3-a). The ingredients are then mixed using a shovel until a homogenous mixture is attained (Figure 3-b). A small crater or hole is created in the center of the heap using the shovel (Figure 3-c), and the Portland composite cement is added (Figure 3-d). The ingredients are thoroughly mixed, working around the heap and turning the mixture over until a consistent mixture is achieved. Afterwards, a deep crater is formed on top of the heap, and water is added (Figure 3-e). The materials from the sides of the heap are then incorporated into the central crater while continuously turning to ensure an even distribution of water (Figure 3-f). This process is repeated until a workable mixture is obtained (as shown in Figures 3-g to 3-i). The entire mixing process typically takes around 20 to 25 minutes to complete.

Figure 3. Visual representation of the hand mixing process: (a) spreading out aggregates; (b) blending with a shovel; (c) creating a central crater in the heap; (d) adding binder; (e) forming crater and adding water; (f) mixing for uniform water distribution in the mixture; (g) workable mixture from a batch; (k) workable mixture from a different batch; (i) workable mixture from another batch; (j) measuring temperature; (k) measuring slump; and (l) preparing cylindrical specimens.

For the study, a total of eight on-site concrete batch mixers were recruited, each possessing varying levels of experience ranging from 5 to over 20 years in the field. Among these, five batch mixers were selected for the primary investigation, while the remaining three were tasked with batching the same mixture to assess the impact of the mixers' experience on the properties of the concrete batches. All the batch mixers followed the common practice observed on construction sites in Morocco and many developing countries, which involved using wheelbarrows to estimate the quantity of mixture ingredients needed. Additionally, in some cases, the quantity of mixture ingredients was estimated visually by the batch mixers.

2.5.2. Machine Mixing

Machine mixing refers to the process of blending concrete mixture ingredients with a mixer machine (such as batch mixer (i.e., drum mixer or pan-type mixer) or continuous mixers). In the current study, the batches were prepared using a pan mixer with a capacity ranging from 70 liters to 120 liters, following the same sequence. The dry constituents were first introduced into the mixer and mixed for about 30 seconds to homogenize the dry ingredients (Figure 4-a). The mixing water was then progressively added and mixing continued for about ten minutes.

Figure 4. Machine mixing: (a) dry constituents in the pan mixer; (b) mixing of constituents progressively; (c) workable mixture and (d) prepared specimens

2.5.3. Sampling

For each mixture, the required number of 300 × 150 mm cylindrical specimens were prepared for the density tests, the compressive strength tests, the porosity tests, and the in-place binder content tests. Prior to pouring, the inner surfaces of the molds were coated with a thin film of oil to prevent the concrete from adhering to the mold. The samples were then covered to protect against rapid evaporation and to avoid contamination after casting.

2.6. Test Program

In the present study, the fresh property tests, compressive strength test, and porosity accessible to water were measured. After mixing the components, the testing of fresh concrete properties was run in parallel.

2.6.1.Workability Test

A slump test was performed immediately after each batch to measure the workability of the fresh concrete following [38]. The slump cone and base plate were dampened and placed on a flat, firm surface. The mold was filled with fresh concrete in three roughly equal layers, each consolidated with 25 strokes from a 16-mm-diameter tamping rod. After compacting, the surface of the fresh concrete was struck off by means of a sawing and rolling motion with the tamping rod. Then the mold was removed from the concrete by raising it carefully in a vertical direction. Immediately after the removal of the slump cone, the slump was measured and recorded by determining the difference between the height of the mold and that of the highest point of the slumped test mixture (see Figure 3-k).

2.6.2. Temperature of Fresh Concrete

The temperature after each batch of concrete was also tested following ASTM C1064 [39] to ensure the concrete's conformity with standard temperature specifications.

2.6.3. Density of Concrete

The density test for fresh concrete mixtures was carried out in accordance with the European standard EN 12350-6 standard [40]. A cylindrical specimen measuring 300×150 mm with a known volume, v, was weighed to determine its mass and the value was recorded as m_1. The cylinder was then filled with fresh concrete in two approximately equal layers. Each layer was then compacted with tamping rod to achieve full compaction, then the surface was levelled, and the outside of the cylinder was wiped clean. The cylinder with its contents was reweighed to determine its mass and the value was recorded as m_2. The fresh density, ρ, was calculated by dividing the net mass by the volume (v), using the expression: $\rho = (m_2 - m_1)/v$.

2.6.4. Air Content

The air content in the fresh concrete was measured in accordance with NF EN 12350-7 [41] (equivalent to ASTM C231 [42]). The fresh concrete was filled into the bowl in three equal layers, and each layer was rodded uniformly 25 times with a 16-mm-diameter tamping rod. After rodding, the side of the bowl was tapped with a mallet to eliminate entrapped air along the sides and close any holes left by the tamping rod. Excess concrete was smoothed off, and the bowl's rim was cleaned. The cover of the air meter was securely clamped, and both petcocks were opened. The air valve between the air chamber and the bowl was then closed. Using a syringe, water was injected through one petcock until it exited the other. The air bleeder valve on the chamber air was closed, and air was pumped into the air chamber until the gauge hand was on the initial pressure line. The petcocks were then closed, and the main air valve was opened. The air content on the dial on the top of the meter was then read after lightly tapping the gauge to stabilize the dial.

2.6.5. Compressive Strength

The compressive strength of concrete mixtures was evaluated on 300×150 mm cylindrical specimens in accordance with the EN 12390-3 standard [43] at the ages of 7 and 28 days. At least three specimens were prepared for each of the fifteen investigated mixtures to carry out the compressive strength tests (see Figure 3-l). All moulds were filled with fresh concrete in approximately three equal layers and each layer was rodded uniformly 25 times with 16 mm diameter tamping rod, followed by trowelling the exposed surface to a clean finish. The cast specimens were kept in their moulds, protected with plastic sheets and moist under laboratory environment at 20±5°C for the first 24 h then demoulded. After demoulding, the specimens were moist cured in water (at a temperature of 20±5 °C and 100% relative humidity) until the specified test age. The compressive strength using the expression $f_c = F_c/\text{A}$, where f_c is the compressive strength (MPa), F_c is the maximum load at fracture (N), and A is the specimen cross-sectional area (mm^2).

2.6.6. Porosity

The total pore volume of specimens with 100 mm in diameter and 50 mm in height after 28 days of moist curing was determined by measuring the porosity accessible to water via the French NF P18-459 standard [44]. The specimens were placed in a desiccator and after 4 hours, maintaining the vacuum pressure at 0.25 bar, they were submerged in water covering up to half height for about 48 hours. Then they were removed from the vacuum unit and then weighed in air to determine the saturated surface-dry mass (recorded as m_{air}) and in water hydrostatic weighing to determine hydrostatic mass (recorded as m_{water}). The specimens were then oven dried at 105 °C to a constant mass (recorded as m_{dry}). The porosity accessible to water (p) was determined as the average of values measured on three specimens using the expression: $\mathrm{P} = (m_{air} - m_{dry}/m_{air} - m_{water}) \times 100$.

2.6.7. In-place Binder Content

Soluble silica content method: This technique involves comparing the amount of SiO_2 in the concrete after nitric acid exposure with the soluble SiO_2 content in the corresponding cement [45, 46]. In this test, slices from 28-day cured concrete specimens were crushed and sieved at 315 µm. For each mixture, 1 g of the powdered sample was diluted in a nitric acid solution (diluted at 1/50), and the resulting solution was filtered. The filter content was then incinerated at 1000°C to obtain the insoluble residue [45]. The ICP-AES (inductively coupled plasma atomic emission spectrometry) technique was then used to determine the SiO_2 content in the insoluble residue. The cement content, as a percentage, was calculated by dividing SiO_2 in the concrete after nitric acid treatment by the SiO_2 in the cement.

Inert method: The total siliceous and calcareous aggregates, along with the bound water in the cement paste, are determined by considering the sum of the insoluble fraction (INS), the loss on ignition (LOI), and the calcium oxide (CaO) content bound to the carbon dioxide (CO_2). The cement content is calculated as the difference to 100 of these sums [46]. To determine the INS content which corresponds to the siliceous aggregates: a 1g (m_1) sample was calcined at 450 °C. The resulting sample was then placed in a 250 mL beaker, and 100 mL of distilled water was added and stirred for 2 minutes. Afterward, 40 mL of nitric acid solution (≈ 1.2 mol/L) and 60 mL of distilled water was added. Stirring continued for 30 minutes at room temperature with the pH level maintained at 1 for 15 minutes. The solution was left to settle for about 24 hours, ensuring pH level remained at 1. The residue was filtered using an ashless filter and washed with distilled water. The filter and residue were placed in a platinum crucible and heated in an oven set at 975 ± 25 °C for 30 minutes. The crucible was left to cool in a desiccator and then weighed. This process was repeated until a constant mass (m_2) is achieved. The percentage of INS was calculated using the expression: $INS = (m_2/m_1) \times 100$.

Next, the LOI at 975 °C was determined. For this test, a sample 1g (m_3) was placed in a crucible and dried at 105±5 °C. The crucible with the sample was placed in an oven set at 975±25 °C for 15 minutes and then left to cool in a desiccator at room temperature. The process was repeated until a constant mass was reached, and the final mass is recorded as m_4. The LOI at 975 °C was calculated as: $LOI = (m_3 - m_4/m_3) \times 100$. To determine the CO_2 content, the loss on ignition at 500 °C (LOI') was determined. Here, a sample weighing about 1 g (m_5) was placed in a crucible and dried at 80±3°C. Then the crucible with the dried sample was placed in an oven set at 500±25 °C for 15 minutes and then allowed to cool in a desiccator. The process was repeated until a constant mass was reached, and the final mass is recorded as m_6. The LOI at 500 °C was calculated as: $LOI' = (m_5 - m_6/m_5) \times 100$. The CO_2 content corresponds to the difference between the LOI at 975 °C and the LOI at 500 °C. thus, $\mathrm{CO_2} = LOI - LOI'$).

Finally, if the CO_2 content > 1%, then the cement content as a percentage is o determined as:

$$\text{Cement content:} = 100 - (INS + LOI + 1.27 \times [CO_{2eq} - 1]) \tag{3}$$

where the coefficient 1.27 represents the ratio between the molar mass of CaO (56.0774 g/mol) to that of CO_2 (44.01 g/mol). However, if the CO_2 content < 1%, the cement content as a percentage is o determined using the expression:

$$\text{Cement content:} = 100 - (INS + LOI) \tag{4}$$

2.7. Scanning Electron Microscope

The assessment of the homogeneity of the mixing processes and the compactness of concrete structures were also performed using the FEI FEG 450 field emission GUN Scanning Electron Microscope (SEM). The SEM micrographs were carried out at the Research Center for Materials and Thematic Energy (CRT-M&E), at the Faculty of Sciences Ben M'Sik, Department of Chemistry, HASSAN II University of Casablanca, Morocco.

3. Results and Discussion

3.1. Characteristics of Aggregates and Particle Size Distributions of the Fine Aggregates

The physical and chemical characteristics of the dune sands, river sand, crushed limestone, and coarse aggregates are detailed in Tables 5 and 6. Additionally, the gradation or particle size distribution curves expressed in terms of the cumulative percentage passing each sieve are presented in Figure 5. As can be seen in Table 5, the maximum particle sizes of the dune sands varied from 1 to 5 mm, while the river sand had a maximum particle size of 5 mm, and the crushed limestone had a maximum size of 4 mm. Thus, only the crushed limestone falls within the acceptable range of

0 to 4 mm [24]. Although dune sands and river sand slightly exceeded the standard limit of 4 mm, this deviation (less than 1%) is deemed acceptable for practical concrete production [24, 47]. The results also demonstrate that the river sand and the crushed limestone met the ASTM fineness modulus criteria of 2.3 to 3.1 [31] and the NM EN12620 criteria of 1.5 to 2.8 for category A aggregates [25]. In contrast, the dune sands are superfine, with fineness modulus values ranging from 0.9 to 1.0. While these values comply with the NM EN12620 criteria for category D aggregates and can be classified as fine-grain sands [25], they fall outside the range suggested in ASTM C33 [31] for construction applications. Indeed, several researchers [13, 14, 48] have also observed that dune sands are superfine and do not meet the upper and lower limits of fine aggregates used in concrete. Thus, a correction of the fineness modulus is often necessary for dune sands to meet the requirements for concrete preparation [14, 48]. The fineness modulus of dune sand can be improved by incorporating river sand, coarse sand, or manufactured sand in various proportions [48]. Refer to Section 2.2.1 for detailed discussion.

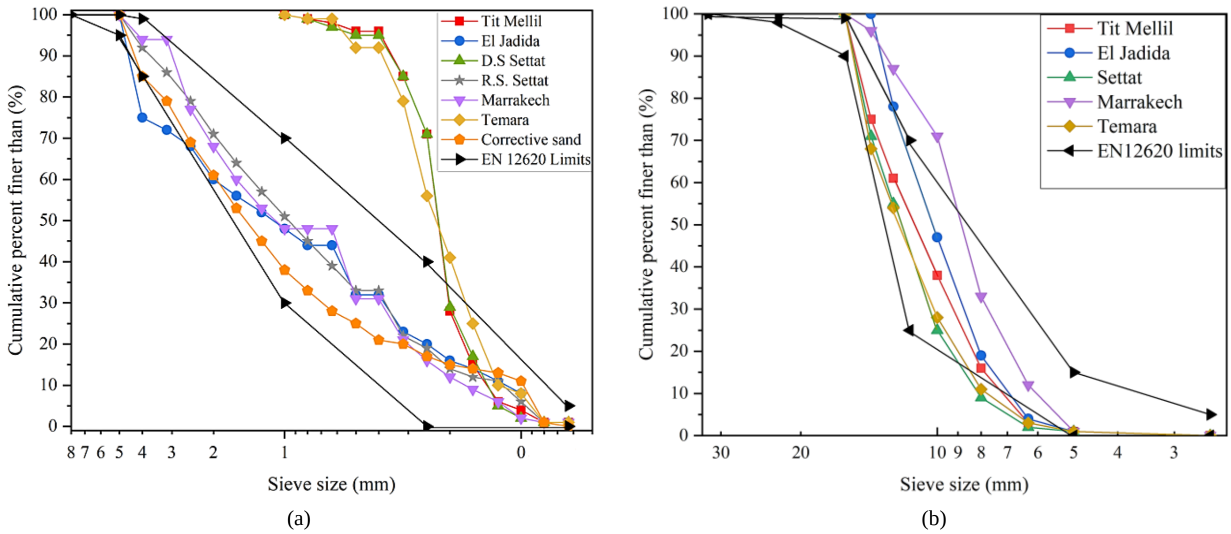


Figure 5. Particle size distribution curves used in the study: (a) fine aggregates and (b) coarse aggregates

Table 5. Physical, mechanical, and chemical properties of the sands

Properties	Tit Mellil	El Jadida	Settat		Marrakech	Temara	Crushed limestone
	Dune sand	Dune sand	Dune sand	River sand	Dune sand	Dune sand	
Maximum size, mm	1	5	1	5	5	1	4
Fineness modulus	1.0	1.0	0.9	2.9	1.0	1.0	3.0
Fines, %	2.5	8.0	5.0	2.8	5.0	5.6	9.8
Density, kg/m^3	2720	2720	2750	2730	2710	2710	2700
Water absorption, %	0.6	2.3	1.9	1.5	1.5	0.7	2.1
Sand equivalent, %	50	30	80	25	80	60	70
Methylene blue, g/kg	0.50	0.75	0.50	2.50	0.50	0.50	0.75
Chloride, %	0.0159	0.0562	0.0065	0.0235	0.0081	0.0098	0.0084
Sulfate, %	0.1170	0.2710	0.0480	0.1130	0.0550	0.0640	0.1100

It can be seen in Table 5 that the fine content of all the sands met the standard allowable limit of 10% for category A aggregates [25]. The sand from Tit Mellil had the lowest fines content of 2.5%, while the sand from El Jadida and the crushed sand had the highest fines content of 8.0% and 9.8%, respectively. Additionally, the absorption of all the sands was below the recommended limit of 2.5 to 3% for fine aggregates in concrete [6, 26]. The dune sand from Tit Mellil had the lowest absorption at 0.6%, while El Jadida sand had the highest absorption at 2.3%. Furthermore, all the sands fell within the range of normal weight aggregate as indicated by their density (i.e., 2700 to 2750 kg/m^3). It is noteworthy that the dune sands from Settat and Marrakech, along with the crushed sand, had higher sand equivalent values (70–80%), indicating cleaner fine aggregates with minimal dust or clay-like content. However, the Tit Mellil and Temara dune sands, with sand equivalent values of 50% and 60%, respectively, did not meet the criteria for category A aggregates (minimum of 65% [27]), but fell within the 60% threshold for category D aggregates, indicating their slightly clayey nature. Similarly, the El Jadida dune sand and the Settat river sand exhibited very low sand equivalent values of 30% and 25%, significantly below the 60% threshold, making them unfit for concrete production due to their unclean nature. The methylene blue value obtained for both the dune sands and crushed sand was below the admissible limit (i.e., < 1.5 g/kg), whereas the river sand exceeded the permissible limit [28]. The chloride and sulfate values obtained for all the types of sand were within acceptable limits [29].

Regarding particle size distributions, Figure 5 shows that the river sand and dune sands from El Jadida and Marrakech are well graded and fall within the standard limit curves, making them suitable for concreting works. However, the dune sands from Tit Mellil, Settat, and Temara are finer than permitted by the standard specifications, rendering them unsuitable for construction use. Consequently, a correction of the grain size distribution is necessary for the sands from these regions when designing concrete for construction applications.

3.2. Characteristics of Aggregates and Particle Size Distributions of the Coarse Aggregates

In the case of the coarse aggregates in Table 6, their maximum nominal sizes ranged from 14 mm to 16 mm, which is generally considered satisfactory for construction purposes. The fines content of the coarse aggregates also met the standard allowable limit of 1.5% [25]. Among them, the coarse aggregates from Marrakech had the lowest fines content of 0.2% while that from Tit Mellil had the higher fines content of 1.0%. The density of these coarse aggregates ranged from 2630 to 2740 kg/m^3. All the coarse aggregates also had absorption of less than or equal to 1%, with the coarse aggregate from Temara having the lowest absorption percentage of 0.4%, while those from El Jadida and Marrakech had the highest absorption of 0.8%. Furthermore, the flattening coefficients of the coarse aggregates were very low, ranging from 9% to 13%, which are well below the acceptable limit of 20% for category A aggregates [33]. The Los Angeles abrasion values obtained were also within the acceptable limits of 30% to 50% set in the standard [34]. In terms of chloride and sulfate values, all the coarse aggregates met the admissible criteria [29]. Regarding particle size distributions, Figure 5 clearly illustrate that all the coarse aggregates used for the experiments are well graded and within the standard limit curves, thus suitable for used in construction works. Overall, the results indicate that all the coarse aggregates are well suited for producing high-quality concrete without the need for correction.

Table 6. Physical, mechanical, and chemical properties of the coarse aggregates

Properties	Tit Mellil	El Jadida	Settat	Marrakech	Temara
Maximum size, mm	16	14	16	16	16
Fines, %	1.0	0.6	0.4	0.2	0.8
Density, kg/m^3	2740	2730	2630	2680	2720
Water absorption, %	0.70	0.80	0.60	0.80	0.40
Flattening coefficient, %	13	13	15	9	12
Los Angeles, %	22	20	21	18	23
Chloride, %	0.0253	0.0396	0.0320	0.0121	0.01
Sulfate, %	0.058	0.045	0.213	0.048	0.051

3.2.1.Correction of Fineness Modulus and Particle Size Distribution of Dune Sand

The river sand was deemed unsuitable for concrete production due to its low sand equivalent. Therefore, only the dune sands were corrected. The fineness modulus and particle size distribution of the sand dune were optimized by adding crushed limestone as a partial replacement. After several trials using Equations 1 and 2, the optimal corrected sand was achieved by blending of 75% of crushed limestone with 25% of dune sand to attain the targeted fineness modulus of 2.5. The gradation curve of the corrected dune sand, as shown in Figure 5, also fell within the standard limit curves. The overall results indicate that the mixtures made with corrected sand yielded better results compared to those with uncorrected sands. This finding is consistent with studies by Vouffo et al. [10] and Akhtar et al. [48], which demonstrated that mixtures with corrected sand outperformed those with uncorrected sands. This suggests that fine-graded (unsuitable) sands can be enhanced by adding crushed sand to achieve improved gradations, fineness modulus, and increased compressive strength, making them suitable for use in concrete applications. It is important to mention the dune sand from El Jadida due to its very low sand equivalent value (i.e., 30%) was deemed very unclean and unfit for concrete production and therefore was not corrected.

3.3. The Influence of the Hand Mixing Process on Concrete Quality

As previously indicated, the mixture compositions detailed in Table 4 were derived through estimation of the ingredients used during hand mixing. As expected, the results indicate that machine and hand mixing of identical recipes and ingredients will lead to different concrete mixture compositions (see Tables 3 and 4), and thus varied concrete properties. Furthermore, the results suggest that hand mixing introduces variability in the test results, thereby making reproducibility of the test results difficult. For instance, the ability to determine when a mixture is workable relies on the skill acquired through experience, leading to inconsistencies from one batch to another (see in Figures 3-g to 3-i). Additionally, the overall mixing process can be labour-intensive and time consuming. Thus, the variations between the batches can be partly attributed to the fatigue experienced by batchers after prolonged mixing periods, which sometimes span five or more batches, often continuing until designated tasks of the day is accomplished, such as filling a concrete slab. The use of wheelbarrows and buckets for measuring the concrete ingredients further contributed to the lack of uniformity in the batches. Furthermore, instances of inadequately mixed concrete batches were documented (see Figures 6-a to 6-c). For example, in Figure 6-a, the coarse aggregate and dune sand were not sufficiently blended, while Figure 6-b, shows a batch where the dune sand was not properly integrated into the mixture. Similarly, in Figure 6-c, it can be seen that not all the water added was fully incorporated into the mixture.

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 6. Hand mixed concrete: (a) inadequately mixed batch; (b) uneven mixing of sand; (c) uneven mixing of aggregate and water (d) added water not incorporated into mixture; (e) earth and dirt incorporated into mixture; (f) mixing surface after batching; (g) mixing surface after batching showing materials wasted; and (h) specimen experiencing bleeding.

While it is recommended to use a clean and water-tight platform for the hand mixing process, this guideline was not strictly followed by the batchers in this study. The concrete mixtures were frequently prepared directly on the ground, with little consideration for their quality or cleanliness (see Figures 3-g to 36-i and Figure 6-c). This practice led to the incorporation of earth and dirt into some of the mixtures (see Figure 6-a), potentially contributing to the observed increase in the density of the specific hand-mixed concretes (i.e., Mixtures C1 and C3). Otherwise, the mixing surfaces were not cleared of debris from the preceding batch before spreading aggregates and sands for the subsequent batch, and as such, moisture absorption was also evident in some cases. Additionally, significant material waste, particularly involving binder and fine sand, was observed during the hand mixing process (see Figure 6-g). Climatic conditions, such as strong winds and rain, further exacerbated this waste by causing the loss of fine materials, necessitating the addition of extra binder and sand to compensate for the losses. In the context of the current study, the hand mixing process consumed approximately 5–10% more binder than the machine mixing process. However, only about 3% of this additional binder actually manifested in the final mixture due to the aforementioned loss of fine materials. The poor handling of the fresh concretes after batching also resulted in significant binder loss, leading to extremely low compressive strength and exceedingly porous concretes.

In terms of mixture compositions, it was observed that the binder content of all the mixtures, except for Mixture C1, exceeded the minimum requirement of 310 kg/m^3 specified in the NM 10.1.008 standard [36] for the exposure class XCA2. The lower binder content of Mixture C1 may be attributed to the limited experience of the on-site batcher used. Conversely, the total w/cm ratio of all the hand-mixed concrete exceeded the maximum requirement of 0.60 specified in NM 10.1.008 [36]. This is largely attributed to the practice of continually adding water to the mixture until the desired workability is achieved (based on visual observation). The addition of water primarily serves to ease the mixing process, given its labor-intensive nature. In practice, whenever the concrete appears somewhat dry or becomes challenging to mix, water is introduced. Conversely, if too much water is added, additional binder and sand are incorporated, and vice versa. This did not always translate into high slump values in most cases because some of the water dissolved into the porous mixing surface while others also seeped out of the crater and thus were not mixed into the concrete as previously mentioned (see Figures 6-a and 6-b). Otherwise, this continuous adjustment process made it challenging to accurately replicate the w/cm ratio of the hand-mixed concretes in a laboratory setting, as noted in a prior study [4].

3.4. Workability of the Fresh Concretes

The fresh concrete properties of the mixtures investigated are detailed in Table 7. It can be seen in Table 7 that the slump values recorded immediately after hand mixing were generally high, with the exception of Mixture C2. Such high initial slumps were necessary due to the lengthy on-site casting process, which often involves the vertical casting of elements. Overall, the slump values of the locally designed mixtures (i.e., Mixture C1 to C5) exhibited much higher slump values when machine-mixed (130 to 270 mm) compared to when hand-mixed (40 and 160 mm). This can be attributed to the precision of the batching of mixture ingredients, which were batched mechanically, whereas variations in quantity were more common when the mixtures were batched manually. On the other hand, the slump values of the Dreux-Gorisse mixtures (with and without corrected sand) did not follow any distinct pattern, with the slump values ranging between 110 and 170 mm for both mixing methods. The batch-to-batch variability of these mixtures was also much more reliable compared to the locally designed mixtures. The extremely high slump of Mixture C1 can be somewhat explained by the very low fines percentage of the dune sand used, resulting in fewer finer particles to absorb water in the concrete mixture.

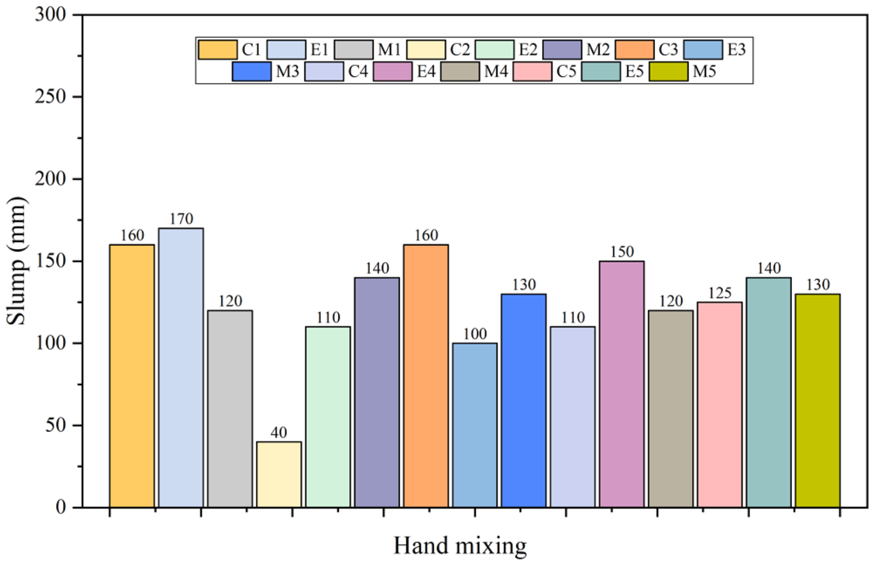
Table 7. Temperature and density of the fresh concrete

Property	Tit Mellil			El Jadida			Settat			Marrakech			Temara		
	C1	E1	M1	C2	E2	M2	C3	E3	M3	C4	E4	M4	C5	E5	M5
Temperature [a], °C	26.8	23.7	23.1	24.7	25.0	24.3	28.1	25.0	24.5	29.3	24.8	25.3	19.1	24.6	23.7
Temperature [b], °C	23.4	21.4	25.0	24.0	27.1	26.5	25.2	22.6	27.3	27.3	20.9	24.9	20.1	25.2	23.4
Density [a], kg/m^3	2360	2340	2350	2360	2360	2410	2560	2330	2370	2240	2340	2400	2290	2480	2380
Density [b], kg/m^3	2220	2400	2370	2310	2370	2370	2440	2230	2330	2220	2360	2350	2240	2390	2370

[a] Hand mixing; [b] Machine mixing.

In general, the mixtures with slump values under 110 mm did not experience bleeding, while those with values between 110 and 130 mm experienced low bleeding. The mixtures with slump values in the range of 130 to 150 mm experienced moderate-low bleeding, while those with values between 150 and 170 mm experienced moderate-high bleeding. The highest bleeding occurred in the mixtures, with slump values ranging from 200 to 270 mm (see Figure 6-d). It is worth noting that the mixtures from the batches with moderate-high to high bleeding also suffered from segregation issues during placement, primarily due to improper handling. This was particularly evident in Mixtures C1, C3, C4, and C5.

It is also worth noting that Mixture C2 exhibited lower slump values irrespective of the mixing method. The hand-mixed mixture C2 recorded the lowest slump at 40 mm, making it difficult to place. The significantly lower slump values may be partly attributed to the unclean nature of dune sand from the El Jadida region and the presence of a very high percentage of fines content (Figure 7). As it is well known, the finer the aggregates, the less workable the concrete [12]. In general, finer particles have a larger surface area, which absorbs more free water present in the concrete mixture and reduces its workability [49].



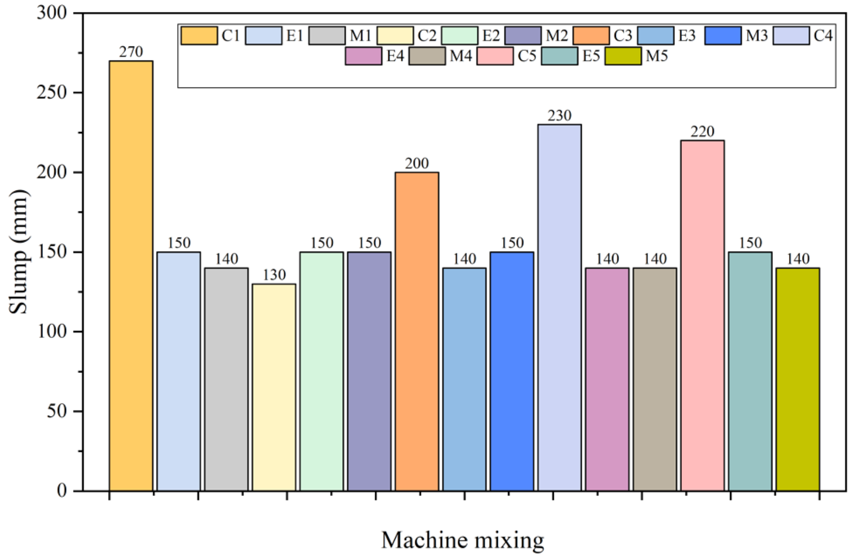


Figure 7. Slump test results of the concrete mixtures tested

3.5. Temperature of Fresh Concrete

The temperature of the fresh concrete varied between 19.1 °C and 29.3 °C at the time of discharge, which falls below the maximum permissible temperature of 35 °C specified in the ACI 305.1-14 standard [50].

3.6. Density of Fresh Concrete

The overall density of the mixtures ranged from 2240 kg/m^3 to 2560 kg/m^3, falling well within the recommended range of 2000 kg/m^3 to 2600 kg/m^3 specified in NM 10.1.008 [36]. The density of both the local and Dreux-Gorisse mixtures did not follow any particular pattern. However, an increase in fresh concrete density of up to 8% was observed in the Dreux-Gorisse mixtures when compared to the local mixtures used in El Jadida, Marrakech, and Temara. This increase can be attributed to the decrease in the w/cm ratio, as higher w/cm ratios should typically lead to lower density. In contrast, a decrease in density ranging from 5% to 9% was observed when compared to the local mixtures used in Settat. This decrease can be attributed to the reduction in binder content, leading to an increase in the total aggregate content. For the Tit Mellil mixtures, a slight decrease in density (less than 1%) was observed in the mixtures made with the corrected sands when hand-mixed, while an increase in density (7% to 8%) was observed when machine-mixed compared to the control mixtures. This difference is attributed to the dirt incorporated into the mixtures during hand mixing, which increases the weight (see Figure 3-j).

Regarding the two mixing methods, a slight decrease in density of about 1% to 6% was observed for the control mixtures after machine mixing compared with manual mixing. However, conflicting results were found for the corresponding mixtures designed based on the Dreux-Gorisse method. While some mixtures were consistent with the trend observed in the locally designed mixtures (i.e., Mixtures E1, E2, E4, and M1), others showed an opposite trend (i.e., Mixtures E3, E5, M2, M3, M4, and M5), with higher density observed in hand-mixed concretes compared to machine-mixed concretes. This variability can be attributed to the inherent variability associated with the hand mixing method.

3.7. Air Content of Fresh Concretes

The air content measurements yielded values of 2.1%, 3.0%, 2.5%, 2.5%, and 3.0% for the control mixtures C1, C2, C3, C4, and C5, respectively, when hand mixed. In the case of machine-mixed Dreux-Gorisse concretes, the values ranged from 2.0% to 3.0%. These values are normal for such non-air-entrained mixtures in the absence of admixtures. It should be mentioned that the air contents of the control mixtures were only measured after manual mixing, whereas for the Dreux-Gorisse mixtures, the air contents were measured only during the trial phase after mixing mechanically. Unfortunately, due to damage sustained by the concrete air content meter during the study, further measurements were not possible. However, there was no change in the air content in the mixtures tested before the damage occurred to the concrete air content meter; thus, values obtained before the damage were deemed sufficient for drawing conclusions.

Furthermore, since no admixtures were used, and the mixtures are non-air-entrained and not expected to be exposed to cycles of freezing and thawing; therefore, air content testing may not be necessary for such concretes unless specifically mandated by the construction documents, as per the interpretation of ASTM C94.

3.8. Compressive Strength

The results of the compressive strength tests performed on the mixtures investigated at curing ages of 7 and 28 days are summarized in Table 8. Individual results are presented, such as to appreciate the level of homogeneity achieved during batching. The coefficient of variation (COV), which represents the overall variation in the measured individual cylinders, ranged from approximately 1.4% to 6.5% for the hand-mixed samples and from 0.9% to 4.8% for the machine-mixed samples, all of which fall within the acceptable range. The overall results show that strength is a function of the w/cm ratio, with an increase in strength with age noted in all specimens [3, 5, 7, 14, 19, 51–53]. Additionally, the strength values seem to be independent of the cement content [51]. As expected, the hand-mixed concrete mixtures exhibited lower 28-day strengths compared to the laboratory-produced concrete, which is consistent with previous investigations [4, 6]. Indeed, the compressive strength values of all the hand-mixed concretes fell below the recommended minimum of 25 MPa specified in the standard [36] for structural use in the XCA2 exposure class. Previous studies [19] also found that hand-mixed concrete typically fails to meet the designed target strength. The overall lower compressive strength values of the hand-mixed concretes can be attributed, at least in part, to inadequate mixing and poor handling practices during and after batching. With regards to machine-mixed concretes, the control mixtures, Mixture C1 to C5, failed to meet the minimum strength of 25 MPa required for structural use, while Mixture E1 to E and M1 to M5 exceeded the minimum recommended 25 MPa. This indicates that using machine mixing methods can effectively improve the compressive strength of the concrete mixtures.

Table 8. Compressive strength of the mixtures tested (unit: MPa)

Region	Mixtures	Individual 7-d results		$f_{c-7d\ avg.}$		Individual 28-d results		$f_{c-28d\ avg.}$	
		Hand	Machine	Hand	Machine	Hand	Machine	Hand	Machine
Tit Mellil	C1	6.0	8.0			8.0	9.2		
		7.0	8.0	6.7	7.7	8.0	9.5	8.2	9.6
		7.0	7.0			8.5	10.1		
	E1	13.1	21.0			18.2	26.8		
		13.5	21.0	13.5	20.7	19.0	28.1	18.4	27.0
		14.0	20.0			18.0	26.3		
	M1	17.0	24.0			21.5	29.3		
		17.0	22.0	17.6	23.0	22.8	30.1	22.4	29.7
		19.0	23.0			23.0	29.7		
El Jadida	C2	11.0	11.0			16.1	17.8		
		14.0	12.0	12.3	12.0	16.9	18.0	16.7	18.0
		12.0	13.0			17.0	18.1		
	E2	13.0	19.0			18.2	24.5		
		11.0	19.0	12.3	19.3	17.1	25.7	17.1	24.8
		13.0	20.0			16.1	24.3		
	M2	14.5	21.5			21.5	27.4		
		14.0	22.0	14.5	21.5	20.1	28.1	20.9	27.7
		15.0	21.0			21.0	27.6		
Settat	C3	11.0	15.0			18.4	23.2		
		14.0	16.0	13.0	16.0	17.8	22.8	17.4	22.7
		14.0	17.0			16.2	22.1		
	E3	13.0	20.0			17.3	25.1		
		13.5	20.0	12.8	19.3	19.1	24.8	18.1	24.7
		12.0	18.0			18.0	24.3		
	M3	17.0	21.0			22.2	28.1		
		16.0	24.0	16.5	22.0	21.1	29.3	21.8	28.3
		16.5	21.0			22.1	27.6		

Marrakech	C4	14.0 16.0 15.0	18.0 18.0 16.0	15.0	17.3	18.1 19.2 18.5	25.0 23.0 25.0	18.6	24.3
	E4	15.0 13.0 14.0	20.0 23.0 22.0	14	21.7	20.3 18.1 19.9	26.5 28.0 26.0	19.4	26.8
	M4	18.5 18.0 19.0	23.0 25.0 24.0	18.5	24.0	22.9 22.0 23.2	31.0 30.0 29.4	22.7	30.1
Temara	C5	17.0 16.0 17.0	15.0 15.0 16.0	16.7	15.3	20.0 20.9 21.1	22.3 21.8 22.9	20.7	22.3
	E5	13.0 13.0 13.0	22.0 20.0 20.0	13	20.7	17.6 17.9 17.4	26.6 25.1 26.3	17.6	26.0
	M5	18.0 17.0 17.0	24.0 23.1 22.9	17.3	23.3	22.4 23.1 21.8	30.2 28.4 29.1	22.4	29.2

If one compares the two mixing methods, it is evident that the locally designed mixtures consistently yielded lower 28-day compressive strength values compared to the corresponding Dreux-Gorisse mixtures, except for Mixture C5 when hand-mixed (which was higher than Mixture E5). The reduction in strength reached up to 56% and 64% for the hand-mixed concretes when compared to the Dreux-Gorisse mixtures with uncorrected and corrected sand, respectively. Similarly, for the machine-mixed concretes, the reduction in strength reached up to 65% and 68% when compared to mixtures with uncorrected and corrected sand, respectively. The lower strength of the locally designed mixtures can be attributed to the combined effect of improper proportioning and mixing of the ingredients, leading to inadequate hydration in portions of the mixture. Otherwise, the compressive strength values of all the locally designed mixtures were below the minimum strength of 25 MPa for structural use, irrespective of the mixing method. However, mixtures C3, C4, and C5 with strength values between 22.7 to 24.3 MPa when machine-mixed could also be acceptable for structural use. For Dreux-Gorisse mixtures, the compressive strength values of the mixtures hand-cast were below 25 MPa, while those machine-mixed met the minimum strength requirement of 25 MPa.

Furthermore, among the Dreux-Gorisse mixtures, the mixtures made with the corrected sands consistently achieved higher compressive strength values than those made with the uncorrected sand. The improvements in strength ranged from 17% to 27% for the hand-mixed concretes and from 10% to 15% for the machine-mixed concretes. The increase in strength is attributed to the reduction in the dune sand content (≈ 75% reduction). In general, a decrease in sand dune content decreases the surface area of the fine aggregates, requiring more paste to coat the surface of the aggregates [12]. The addition of crushed sand also improved the increase in finesse modulus of the corrected sand, which increased compressive strength. Previous studies also found that an increase in the finesse modulus of blended sand increased strength [6].

Otherwise, it was noted that the 7-day compressive strength values were about 69% to 82% of the 28-day compressive strength values.

3.9. Porosity

The results of the porosity tests performed on the concrete mixtures after 28 days of moist curing are presented in Figure 8. The results demonstrate that mixtures with a higher w/cm ratio tend to exhibit higher porosity, which is consistent with prior research [5]. Indeed, Mixture C1, characterized by the highest w/cm ratio and lowest binder content, exhibited the highest porosity among the tested mixtures. It can be seen in Figure 8 that the control mixtures recorded higher porosity values (ranging from18.6% to 23.5%) than the corresponding Dreux-Gorisse mixtures (ranging from 18.5% to 19.2% for the mixtures with uncorrected sand and 14.1% to 17.7% for the mixtures with corrected sand). This discrepancy is likely due to improper ingredient proportioning in the control mixtures. For the hand-mixed concretes, a reduction in porosity of up to about 18% was observed with the Dreux-Gorisse mixtures made with uncorrected sand when compared to the control mixtures, and a more substantial reduction of about 28% when compared to mixtures with corrected sand. In the case of the machine-mixed concretes, the reduction in porosity reached about 13% and 32%, respectively, for the Dreux-Gorisse mixtures with uncorrected and corrected sand when compared to the control mixtures.

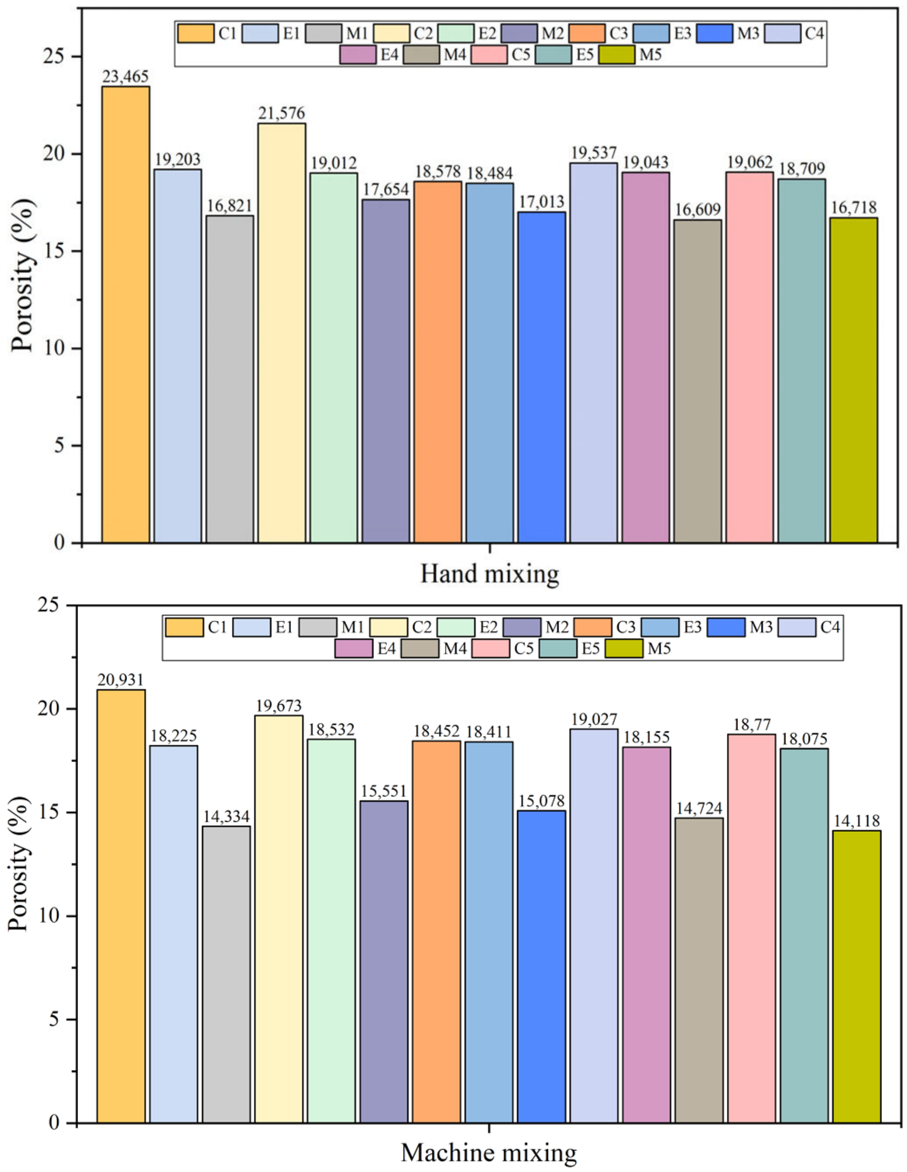
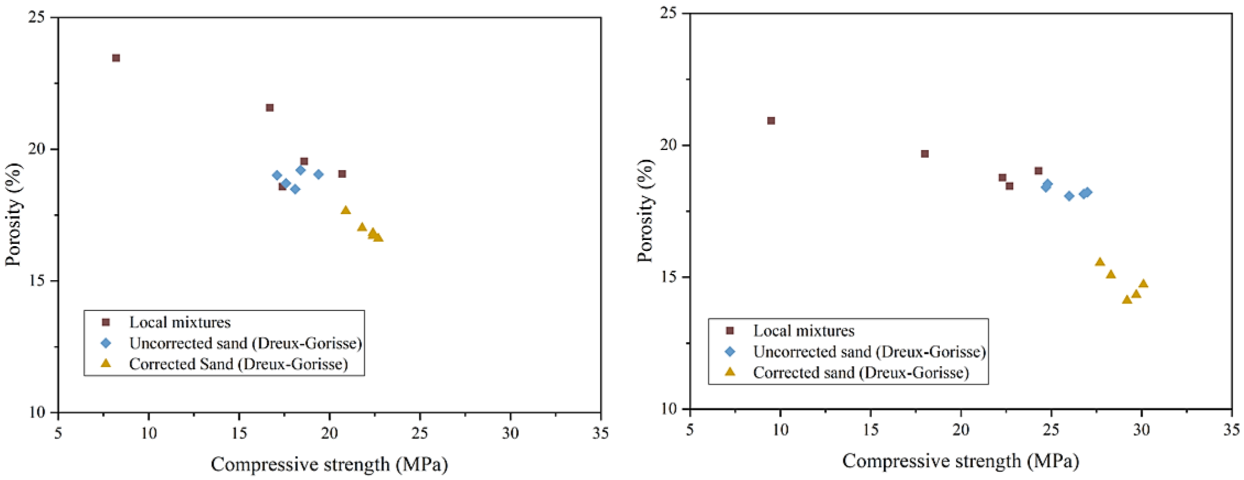


Figure 8. Porosity of accessible water of the concrete mixtures tested

Furthermore, it was observed that among the Dreux-Gorisse mixtures, those formulated with corrected sand exhibited lower porosity than the mixtures with uncorrected sand. The improvements in porosity ranged from 7% to 13% for the hand-mixed concretes and from 16% to 22% for the machine-mixed concretes. Additionally, a noticeable correlation seems to exist between the mixing process and porosity. For instance, in contrast to hand mixing, machine mixing resulted in a reduction in porosity of up to about 11% for the control mixtures, around 5% for the mixtures with uncorrected sand, and 16% for the mixtures with corrected sand. Again, the high porosity of the hand-mixed concrete is attributed to the mixing process using shovels and the poor handling of the hand-batched concrete, which resulted in significant binder and fine material loss.

It is worth noting that the porosity limits for the exposure classes XC3 and XC4 [37] (or XCA2 in the Moroccan standard NM 10.1.008 [36]) are 14.5% and 15%, respectively [54]. Thus, only the mixtures formulated with the corrected sand that were mechanically mixed fell within the prescribed limits. Additionally, it should be mentioned that in cases where excessive bleeding was observed (see Figure 6-h), a corresponding increase in porosity was observed, as bleeding contributes to an increased w/cm ratio in that particular region.

Furthermore, the compressive strength versus porosity graph is presented in Figure 9 to assess the suitability of existing expressions relating to strength and porosity. The individual results for each mixture demonstrate an inverse relationship, indicating that higher porosity is associated with a lower compressive strength of concrete. This is expected, as an increase in void space leads to a decrease in the elasticity modulus and strength of concrete. However, there is no overall relationship that holds true for all mixtures. This confirms the findings of other researchers [5, 53].



(a) Hand mixing (b) Machine mixing

Figure 9. Relationship between porosity and compressive strength

3.10. In-place Binder Content

The results of the in-place binder content of the concrete mixtures tested after 28 days of curing, along with the main tracer elements, are presented in Tables 9 and 10 for the hand-mixed and machine mixed, respectively. It should be mentioned that the percentage of binder content obtained from both the soluble silica content and inert methods assumes that the binder is primarily composed of clinker (i.e., 100%). Therefore, a correction was made based on the binder used. The percentage of in-place binder was subsequently converted to kg/m^3 by multiplying it by the density of the concrete.

Table 9. Main tracers and binder content from the concrete powder samples - Hand mixing

Region	Mixtures	Soluble silica method				Inert method					Average binder (%)	Average binder (kg/m^3)
		Concrete SiO_2 (%)	Binder SiO_2 (%)	Binder (%)	Binder (kg/m^3)	INS (%)	LOI (%)	CO_{2eq} (%)	Binder (%)	Binder (kg/m^3)		
Tit Mellil	C1	0.31	11.71	2.6	62	19.84	35.46	32.59	5.0	117	4	90
	E1	1.24	11.71	10.6	248	34.82	26.77	24.51	10.9	256	11	252
	M1	1.28	11.71	10.9	257	56.15	16.64	14.47	13.3	311	12	284
El Jadida	C2	0.95	11.71	8.1	193	81.09	7.3	3.59	10.6	252	9	222
	E2	1.19	11.71	10.2	240	28.62	29.84	27.77	9.4	222	10	231
	M2	1.15	11.71	9.8	237	64.42	14.01	12.04	9.4	273	11	255
Settat	C3	1.6	10.59	15.1	338	69.8	11.09	6.63	15.3	343	15	341
	E3	1.02	10.59	9.6	225	28.25	29.86	27.81	9.4	231	10	228
	M3	1.07	10.59	10.1	239	77.98	7.5	5.3	11.2	257	11	248
Marrakech	C4	1.48	8.15	18.2	407	69.65	10.16	5.7	18.4	413	18	410
	E4	1.01	8.15	12.4	290	54.95	17.85	15.29	11.1	259	12	275
	M4	1.02	8.15	12.5	300	27.15	29.86	27.62	11.3	270	12	285
Temara	C5	1.21	13.17	9.2	213	18.65	34.6	31.21	10.3	239	10	226
	E5	1.24	13.17	9.4	224	26.64	31.07	27.87	10.0	237	10	231
	M5	1.32	13.17	10.0	239	64.16	12.46	10.49	14.5	344	12	291

Table 10. Main tracers and binder content from the concrete powder samples - Machine mixing

Region	Mixtures	Soluble silica method				Inert method					Average binder (%)	Average binder (kg/m³)
		SiO_2 (%) concrete	SiO_2 (%) binder	Binder (%)	Binder (kg/m³)	INS (%)	LOI (%)	CO_{2eq} (%)	Binder (%)	Binder (kg/m³)		
Tit Mellil	C1	1.24	11.71	10.6	235	52.63	19.67	16.3	10.5	233	11	234
	E1	1.7	11.71	14.5	348	58.6	16.42	11.97	14.7	352	15	350
	M1	1.77	11.71	15.1	358	51.77	18.16	15.85	14.9	353	15	356
El Jadida	C2	1.57	11.71	13.4	310	56.97	17.41	13.17	13.3	308	13	309
	E2	1.72	11.71	14.7	348	49.3	19.81	16.518	14.9	352	15	350
	M2	1.76	11.71	15.0	356	49.94	18.81	16.766	14.9	354	15	355
Settat	C3	1.9	10.59	17.9	438	46.14	20.01	17.61	18.0	439	18	438
	E3	1.71	10.59	16.1	358	47.71	19.93	17.535	15.8	352	16	355
	M3	1.63	10.59	15.4	359	46.73	20.76	17.988	15.1	353	15	356
Marrakech	C4	1.67	8.15	20.5	455	54.36	15.53	12.315	20.7	461	21	458
	E4	1.21	8.15	14.8	349	54.65	17.25	13.91	15.0	353	15	351
	M4	1.24	8.15	15.2	359	55.82	16.79	13.275	15.1	355	15	357
Temara	C5	2.41	13.17	18.3	410	54.78	15.42	13.4	18.5	414	18	412
	E5	1.99	13.17	15.1	357	55.93	16.62	13.579	14.7	352	15	354
	M5	1.92	13.17	14.6	348	55.06	16.39	14.318	15.0	355	15	352

As expected, the results in Tables 9 and 10 show that the hand-mixed concretes exhibited significantly higher binder losses compared to the machine-mixed concretes, due in part to the uniform and homogeneous mixing achieved through mechanical mixing processes. Analysis of the hand-mixed control concretes revealed that the binder losses ranged from 14% to 75% when assessed using the soluble silica method, and about 3% to 53% when evaluated using the inert method. Similarly, the Dreux-Gorisse mixtures with uncorrected sand recorded binder losses ranging from 19% to 38% based on the soluble silica method and 28% to 41% based on the inert method. For the Dreux-Gorisse mixtures with corrected sand, the binder losses ranged from 17% to 34% for the soluble silica method and 5% to 29% for the inert method.

In contrast, the binder losses were much lower for the machine-mixed concretes, ranging from 2.6% to 6.7% for control mixtures, around 0.3% to 3.3% for the Dreux-Gorisse mixtures with uncorrected sand, and about 0.4% to 3.5% for the Dreux-Gorisse mixtures with corrected sand. These results indicate that the binder losses were significantly higher for the hand-mixed concrete, which again may be mixing process using shovels and the poor handling of the hand-batched concretes. In the case of machine mixing based on both the soluble silica content and inert methods produced similar results.

3.10.1. Concrete De-formulation Methods

Regarding the two de-formulation methods, an analysis of Tables 9 and 10 indicates that in the context of machine mixing, both the soluble silica and inert methods can be used to determine the binder content of concrete with a maximum uncertainty of 1.5%. For the machine-mixed concretes, the variations between the two methods ranged from around 0.3% to 1.2% for the control mixtures, about 1.0% to 1.7% for the Dreux-Gorisse mixtures with uncorrected sand, and roughly 0.6% to 1.8% for the Dreux-Gorisse mixtures with corrected sand. In the context of hand-mixed concretes, it was found that the soluble silica method sometimes tends to either underestimate or overestimate the binder content in comparison to the inert method. For example, the soluble silica method yielded binder content estimates that were about 1.5% to 46.5% lower than those derived from the inert method for the control mixtures that were hand mixed. However, for the Dreux-Gorisse mixtures with uncorrected sand, the soluble silica method produced estimates that were approximately 3.1%, 2.3%, and 5.5% lower for Mixtures E1, E3, and E5, respectively, but 8.0% and 11.9% higher for Mixtures E2 and E4. Conversely, for the Dreux-Gorisse mixtures with corrected sand, the values obtained using the soluble silica method were roughly 17.6%, 13.3%, 6.8%, and 30.7% lower for Mixtures M1, M2, M3, and M5, respectively, when compared to the inert method, but 11.1% higher for Mixture M4.

The uncertainty associated with the hand-mixed measurements ranged from 4.0% to 10.5% for the soluble silica method and from 3.0% to 8.8% for the inert method (except for Mixture C1). Notably, the uncertainty for Mixture C1, with a binder content of 250 kg/m³, was found to be 18.5%. This underscores the observation that the uncertainty associated with measuring the binder content of cast concrete can be influenced by the initial binder content in the mixtures, particularly in cases involving low binder content, as reported in a previous study [45].

The average of the values obtained from two concrete de-formulation methods is indicated in Tables 9 and 10. The difference between the average of the results from the two methods and that of the average result obtained from each method ranged 0.22% to 4.51% for the machine-mixed concrete and from 0.05% to 0.40% for the hand-mixed concrete. Thus, the difference between the two results is less than 10%. According to reference [46], the most probable binder content can be taken as the average values obtained from two concrete de-formulation methods. If the difference between the two results is greater than 10%, it means there are errors in the calculation or assumptions, and some factors related to the concrete or mortar have not been considered, such as material degradation, incorrect assumptions about the type of binder used, silica released by the aggregates, or the presence of dolomitic aggregates. In such cases, before continuing with the calculation, it is essential to establish a mineralogical diagnosis of the concrete [46].

3.11. Influence of Batcher Mixers on Hand-mixed Concrete

A total of nine concrete batches were produced using the same mixture (Mixture C1 in Table 4), with the participation of three different expert on-site concrete batch mixers, as mentioned previously. The experience of the experts was quite variable. The first recruit was a self-trained expert batch mixer with more than twenty (20) years of experience, primarily working in the informal construction sector; the second recruit was a self-trained expert batch mixer with about twelve (12) years of experience, also working in the informal construction sector; and the third recruit was a trained expert batch mixer with formal qualification (i.e., having proper knowledge of concrete mixing techniques) and around eight (8) years of experience, employed by a construction company. Each recruit was tasked with producing three successive batches. The volume of the batches produced varied from 100 to 120 liters. The batch details are reported in Table 11. The coefficient of variation (COV) was calculated to assess whether the results are significantly dependent on the number of batches or the specific expert batchers conducting the hand mixing.

Table 11. In-place composition of the batched concrete mixtures (unit: kg/m^3)

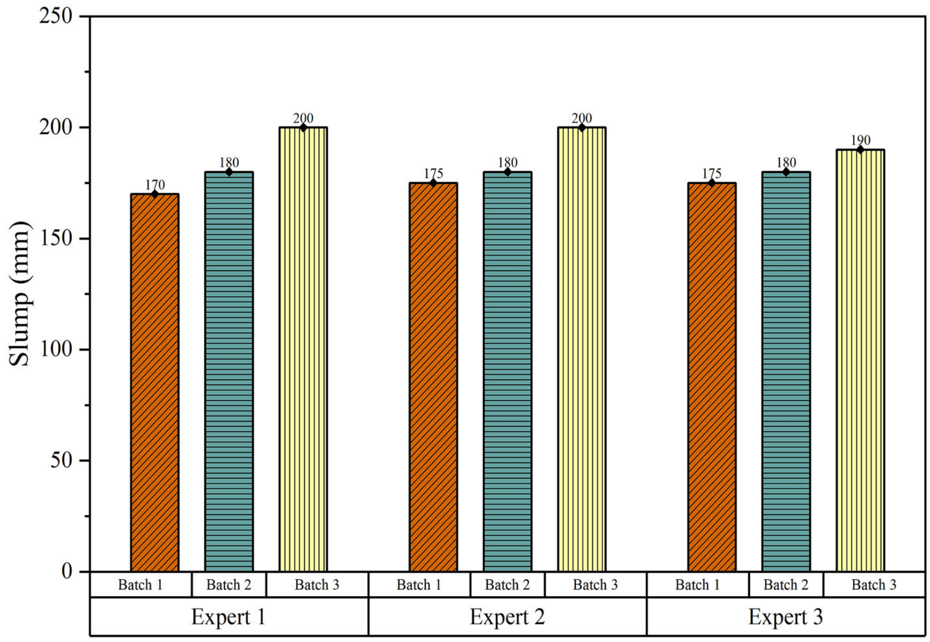
Materials / Property	Expert 1				Expert 2				Expert 3			
	Batch 1	Batch 2	Batch 3	COV	Batch 1	Batch 2	Batch 3	COV	Batch 1	Batch 2	Batch 3	COV
Binder	438	436	437	0.2	455	465	460	1.1	543	494	520	4.7
Coarse aggregates	641	631	640	0.9	558	541	549	1.5	663	692	681	2.2
Dune sand	906	931	916	1.4	873	871	873	0.1	653	768	716	8.1
Mixing water	262	280	280	3.8	318	325	326	1.3	325	296	317	4.8
w/cm	0.60	0.64	0.64	4.0	0.70	0.70	0.71	0.8	0.60	0.60	0.61	1.0

Note: the COV values are expressed as a percentage (%).

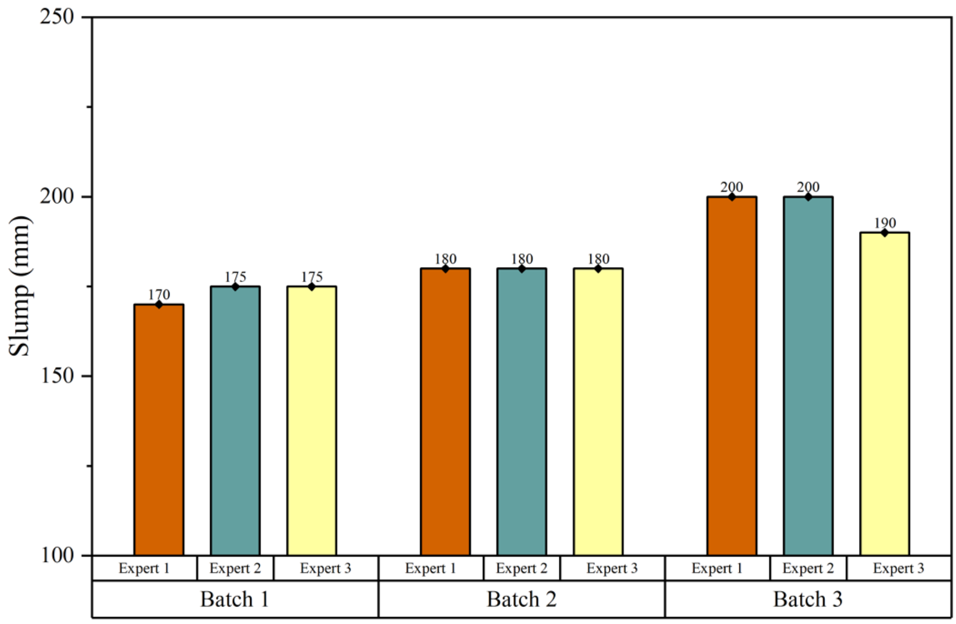
It can be seen in Table 11 that the mixture compositions obtained from the three batches are quite variable, even with the same expert mixer. This variability is evident from the COV values presented and becomes more pronounced when comparing the batches across the three expert batchers. For the binder content, the COV across the batches produced by the individual expert batchers were 11.8%, 6.2%, and 9.1% for batches 1, 2, and 3, respectively. Regarding the coarse aggregate content, the COV values were 8.9%, 12.2%, and 10.8% for batches 1, 2, and 3, respectively. As for the dune sand content, the COV values were 17.0%, 9.6%, and 12.6% for experts 1, 2, and 3, respectively. Furthermore, the COV values for the w/cm ratio were 9.2%, 7.7%, and 7.8% for experts 1, 2, and 3, respectively. Additionally, it was observed that the quality of the in-place concrete is somewhat influenced by the physical strength of the batcher, as hand mixing is a labor-intensive task, and the batchers experienced fatigue after producing three successive batches.

An important observation was that, while the formally trained expert batch mixer (Expert 3) cleaned the mixing surfaces prior to batching, the two self-trained batch mixers (Experts 1 and 2) carried out the batching on the ground without any prior preparation of the mixing surface. This practice resulted in the incorporation of earth and dirt into some of the mixtures, as previously mentioned.

The slump results in Figure 10-a suggest that the experience of the on-site mixer has minimal influence on the workability of concrete, although slight variations were observed among the three experts. The difference in slump between the first and second batches was 10 mm for Expert 1 and 5 mm for Experts 2 and 3. Both self-trained experts (Experts 1 and 2) recorded a 20 mm difference in slump between the second and third batches, while a formally trained expert (Expert 3) recorded a 10 mm difference in slump between the second and third batches. Furthermore, the difference in slump between the first and third batches was 30 mm for Expert 1, 25 mm for Expert 2, and 15 mm for Expert 3. Regarding the consistency among the three batches from the same expert, the COV values were around 8.3%, 7.2%, and 4.2% for Experts 1, 2, and 3, respectively. Remarkably, the variability among the three experts for each batch was surprisingly very low, the COV values were 1.7%, 0.0%, and 2.9% for batches 1, 2, and 3, respectively.



(a)



(b)

Figure 10. Slump test results: (a) variability among batches produced by individual experts, (b) variability among the three experts across each batch cast

Regarding the compressive strength tests, Figure 11 offers a conclusion that everyone would expect: the qualification of the on-site batch mixer is of paramount importance in the production of good-quality concrete when utilizing the hand mixing method of batching. Indeed, there was substantial variability among the three experts for each batch, with COV values ranging from 20.4% and 23.1%, 18.9% and 18.2%, and 24.1% and 21.5% for batches 1, 2, and 3, at 7 and 28 days, respectively. It was observed that the compressive strength values of the batches produced by Expert 3 (formally trained with 8 years of experience) were about 35 to 54% higher than those produced by Expert 1 (self-trained with 20 years of experience) and roughly 25 to 50% higher than those produced by Expert 2 (self-trained with 12 years of experience). Furthermore, Figure 11 reveals that the compressive strength values of the first batches carried out the formally trained expert batch mixer (Expert 3) exceeded the minimum strength of 25 MPa required for structural use. However, the second and third batches fell below the recommended threshold of 25 MPa. The compressive strength values of all three concrete batches carried out by the self-trained expert batch mixers (Experts 1 and 2) were also below the threshold of 25 MPa. Thus, it can be deduced that even a self-trained expert batch mixer with over 20 years of experience does not guarantee the production of good-quality concrete.

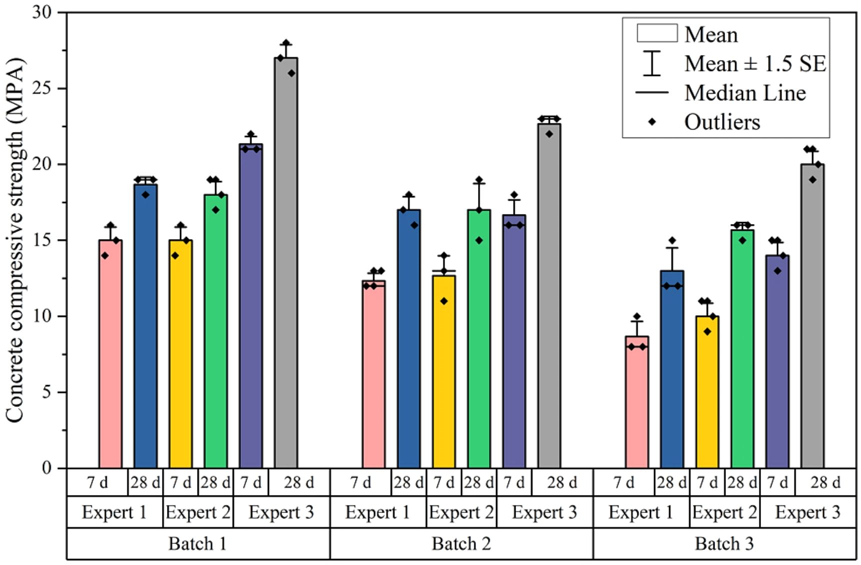


Figure 11. Compressive strength of the batches produced by the expert batch mixers

Furthermore, it can be inferred that carrying out more than one batch using the hand mixing method may result in concrete with inadequate strength, even if the batch mixer is well trained. Indeed, the findings suggest that when hand mixing involves more than two batches, the variability in compressive test results can be quite significant. Among the batches produced by the individual experts, the COV values ranged from 25.0% and 18.7% for the Expert 1, 19.9% and 5.9% for the Expert 2, and 20.3% and 15.1% for the Expert 3, at 7 and 28 days, respectively. This is primarily attributed to the labour-intensive nature of hand mixing approach, as the batchers become fatigued after the first batch, impeding their ability to properly mix the ingredients in the subsequent batches. Indeed, a consistent decrease in compressive strength was observed after each batch, irrespective of the batch mixer. For example, in the case of the Expert 1, there was a decrease in strength of about 20% between batches 1 and 2, around 40% between batches 1 and 3, and about 25% between batches 2 and 3. For Expert 2, a decrease in strength of about 13% was noted between batches 1 and 2, roughly 33% between batches 1 and 3, and around 23% between batches 2 and 3. Similarly, for the Expert 3, a decrease in strength of about 19% was observed between batches 1 and 3, roughly 33% between batches 1 and 3, and about 18% between batches 2 and 3.

3.12. SEM Analyses

In this analysis, the images obtained by scanning electron microscopy (SEM) on the studied samples were subjected to enlargement (×100, 500 µm) to emphasize their morphological aspects. Selected data for the SEM micrographs are presented in Figure 12. The overall SEM images indicate a homogeneous and compact structure for samples taken from Mixtures M1 and M5, which were mechanically mixed. The concrete surface shows no signs of alteration, and therefore, no cracks are observable. However, the results of samples taken from C1, C2, C4, and C5, mixed manually, seem to indicate insufficient mixing. The analysis of micrographs allowed the generation of binary images, where black areas highlight the porosity of the samples. These specimens also appear to exhibit greater porosity. This increase in porosity is not solely due to the cracking of samples but also to the deterioration of the cement paste associated with the release of bound water.

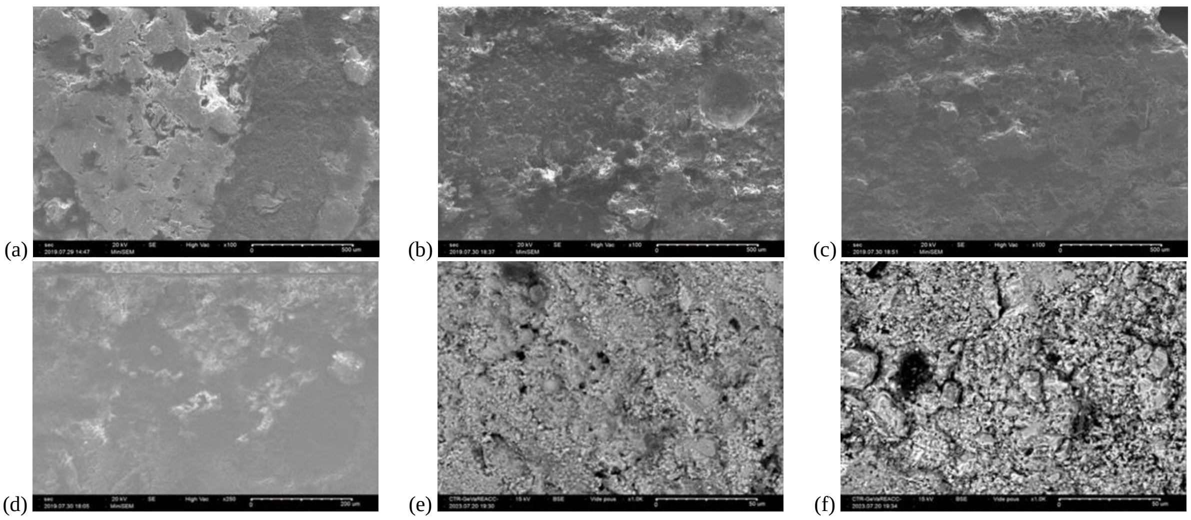


Figure 12. SEM micrographs of the concrete specimens: a) C1 hand mixed; b); C1 hand mixed; c) C4 hand mixed; d) C5 hand mixed; e) M1 machine mixed; f) M5 machine mixed

A similar evolution of porosity is observed, regardless of the technique employed, for each concrete composition. The porosity measured by image analysis is of the same order of magnitude, although generally lower, than the water porosity measurement [55]. This difference is likely due to better water accessibility to pores of very small dimensions compared to those of the resin. Additionally, micrographs taken at low magnifications do not provide a sufficiently fine resolution to highlight low-dimensional porosity. The results thus confirm that machine mixing tends to produce concrete with a more homogeneous microstructure, a more uniform particle distribution, and a reduction in voids. These characteristics can contribute to the better strength and durability of mechanically mixed concrete compared to manually mixed concrete. However, it is important to note that other factors, such as material quality and mixing proportions, can also influence the concrete microstructure.

3.13. Site Observations

Recognizing that many problems in concrete construction on-site are often first identifiable through visual observations, especially by those with specialized expertise [1], several site visits were conducted across a range of construction sites. These sites predominantly utilized informal construction methods and relied heavily on manual concrete production. The primary goal of these visits was to systematically document the prevailing challenges associated with such practices and propose potential approaches to enhance or rectify some of these issues. Figure 13 provides a summary of the most prevalent visual errors consistently observed across the majority of the construction sites visited. The primary observation indicates that the binders, aggregates, and sands are generally not inspected and approved at the source before delivery to the construction sites. Sourcing decisions were predominantly driven by factors such as material cost, availability, and proximity. Proper stockpiling practices were generally lacking, a trend also identified in other regions of Africa [4, 11]. Upon arrival, the materials are stored in exposed areas without adequate cover or protection against rain, sunlight, or wind, in violation of the Moroccan standard NM 10.1.008 [36] (see Figures 13-a and 13-b). This practice frequently results in contamination of the ingredients with various forms of debris, including trash, debris, fuel, paint, and glass (see Figure 13-b). The exposure of the binder and aggregates to humidity from the environment prior to mixing could lead to significant fluctuations in their moisture content, potentially leading to variations in the w/cm ratios across batches, which may influence the properties of the concrete.

Figure 13. Construction practices observed during visits: (a) mixing coarse aggregates, sand and binder in large quantity for the day; (b) adding binder to coarse aggregates and sand for batching on the next day; (c) mixing coarse aggregates, sand and binder in large quantity for the day (d) adding binder to coarse aggregates and sand for batching on the next day; (f) concrete placing in progress; (f) concrete footing; (g) segregation of concrete caused by uneven mixing of coarse aggregate; and (h) unsafe work environment.

Furthermore, heavy rainfall can introduce pollutants onto the construction site, which might come into contact with the exposed aggregate and sand stockpiles. Additionally, lighter aggregate materials are susceptible to being carried away by strong winds or washed away by rain, thereby altering the gradation of the aggregates. Moreover, significant amounts of the binders (often comprising the entire project requirement) are stored on-site, primarily covered with polythene plastic bags. This practice exposes the binder bags to moisture, which can initiate hydration reactions that cause them to solidify into lumps even before the concrete mixing process. Otherwise, a significant portion of the aggregate stockpiles were observed to experience segregation before their use.

Additionally, it was observed that the mixtures were batched using the hand mixing technique, a practice that directly violates NM 10.1.008 [36]. Moreover, the batching of mixtures was carried out in excessively large quantities, as indicated in Figures 13-c and 13-d, leading to challenges in achieving consistent, uniform ingredient blending. The manual use of shovels to blend substantial concrete batches proved to be labor-intensive, particularly when dealing with multiple batches. This subsequently resulted in inconsistencies among the different batches. This issue was noted in the primary study, even when working with smaller batch sizes. Otherwise, the batching and other concreting works were predominantly carried out by unskilled or low-skilled practitioners. Similar observations have been reported in other parts of Africa [11].

Moreover, it was observed that the quantity of water used in concrete mixing was not measured at any of the sites. Instead, the amount of water added was determined through a visual assessment of the mixture's workability and the experience of the batchers, a practice commonly observed in other regions of Africa as well [4, 11]. In most cases, the addition of water was also typically carried out using a water hose (refer to Figure 13-c), making it difficult to accurately measure and control the quantity of water added. This practice frequently resulted in the erosion of binder and sand due to the force exerted by the water pressure.

Another concerning issue observed relates to the practice of the on-site batch mixers preparing for the upcoming day's batching in advance by mixing the dry components in the evening prior (see Figure 13-d). This practice is not advisable due to the moisture sensitivity of binders. Prolonged exposure to air and humidity leads to the absorption of moisture, resulting in the formation of lumps due to pre-hydration. Using binder in such a compromised state would yield inferior concrete quality, ultimately jeopardizing the long-term durability of the constructed building. It was also noted that after the concrete batching process, the concrete is transported using wheelbarrows and then poured and compacted using rudimentary tools such as wooden sticks or metal bars (see Figure 13-e). This method of consolidation is notably weak and insufficient for achieving proper concrete compaction. It was also obvious that most of the mixtures suffered from poor workability due to improper proportioning of mixture ingredients. Insufficient binder was one of the major causes of the poor walkability observed. In some cases, the cause of poor workability was due to too much or too little sand. Most of the sands used were also not well graded, which may also be the cause of the poor workability encountered. Delays in the placement of concrete also resulted in a condition known as under stiffening.

Contrary to the widely acknowledged fact that hand-mixed concrete should not be employed for structural elements as it often leads to poor concrete due to slurry loss and uneven mixing [4], it was observed that the majority of sites visited used hand-mixed concrete for placing the structural elements (Figure 13-f). This practice constitutes a breach of the Moroccan standard NM 10.1.008 [36]. As previously stated, the use of a water hose for water addition frequently resulted in excessive water content, which, when combined with poor concrete handling practices and placement techniques, resulted in visible or honeycombs evident in certain structures after placement (Figure 13-g).

It should be mentioned that no concrete testing, whether for fresh or hardened properties, was conducted at any of the visited sites. Moreover, curing, one of the most important steps of concrete construction, is often disregarded within the informal construction sector. Once the concrete is placed, it is simply left exposed to the open air, irrespective of the climatic conditions (Figure 13-e). As a result, plastic shrinkage cracks were observed on the concrete surface of the concrete elements a few hours after placement. Improper or inadequate curing procedures can result in very weak and porous concrete, which could render it susceptible to abrasion, wear, and the ingress of various harmful substances from the environment [1, 56].

Construction site safety concerns present a significant and pressing challenge, particularly within the informal sector (see Figure 13-h). This challenge stems from a lack of safety awareness, compounded by insufficient training and a limited grasp of safety protocols, particularly among contractors. The track record of construction safety in Morocco, indeed, falls short of international standards. Although precise data is not readily available, the International Labour Organization (ILO) estimates that Morocco experiences an annual construction site-related fatality rate of 47.8 per 100,000 workers [57]. It is plausible, however, that the actual fatality rate surpasses the figure reported by the ILO, given that a considerable number of accidents are unreported or undocumented, especially within the informal sector. For context, the fatal injury rate in the construction (and extraction) industry in the United States in 2021 was 12.3 deaths per 100,000, down from 13.5 deaths per 100,000 in 2020, according to the data from the 2021 Census of Fatal Occupational Injuries report [58]. There is therefore an urgent need to increase the safety of concrete construction sites in Morocco.

4. Conclusion

The present study investigated the impact of sand quality, w/cm, binder properties, mix design methods, and mixing techniques on the fresh and hardened properties of concrete. The results indicated that while the binders and coarse aggregates met standard specifications for concreting, none of the sands met the standard specifications and required correction of grain size distribution and fineness modulus. The river sand from Settat and the dune sand from El Jadida were deemed unsuitable for concrete production due to their low sand equivalent content. However, adjusting the grain size and fineness modulus of dune sands from other regions using Abrams' formulas, by incorporating 75% crushed limestone, rendered them suitable for concrete production. Furthermore, it was found that hand mixing resulted in inadequate mixing, material wastage, lower strength, and increased porosity, whereas machine mixing produced concretes with a more homogeneous microstructure, uniform particle distribution, lower porosity, and higher strength. Scanning electron microscopy (SEM) observations supported these findings, indicating that machine mixing produces concretes with a more homogeneous microstructure, uniform particle distribution, and reduced voids. Hand mixing also introduced variability in test results due to factors such as skill differences, the number of successive hand batches, fatigue, and equipment used. The expertise of the hand-mixed batcher significantly influenced the consistency, porosity, and compressive strength of the concrete. Additionally, both the soluble silica and inert methods were found suitable for determining the binder content of machine-mixed concrete. However, the soluble silica method occasionally exhibited significant variations in hand-mixed concrete compared to the inert method. A combined approach utilizing the average of both methods enhances the overall reliability of the estimated in-place binder content. Observations on construction sites also revealed widespread deviations from recommended guidelines. Issues such as lack of material inspection, stockpiling, ingredient contamination, and inadequate batch mixing contributed to variations in concrete workability, porosity, and compressive strength. Proper consolidation, curing, and quality control testing were largely overlooked on construction sites. Common defects, such as segregation and honeycombs, were also observed at many sites. Furthermore, safety protocols and awareness, particularly in the informal sector, were inadequate, posing significant risks to workers and resulting in a high rate of accidents and fatalities.

4.1. Recommendation

- It is recommended to adopt proper quality control measures by enhancing material inspection, stockpiling procedures, ingredient handling, and batch mixing practices on construction sites.
- Correct sand with undesirable characteristics by incorporating crushed sand using Abrams' formulas.
- Reduce reliance on hand mixing and promote the use of machine mixing for concrete production on construction sites.
- Provide training to personnel involved in concrete production and emphasize the importance of proper mixing techniques for durable concrete.
- Segregation can be controlled to some extent through good aggregate stockpiling practices, increasing the small size of coarse aggregate, using air entrainment agents, dispersing agents, and pozzolanic materials.
- Enhance construction site safety measures and provide training to improve worker awareness and adherence to safety protocols.

5. Declarations

5.1. Author Contributions

Conceptualization, F.H. and B.M.; methodology, F.H. and B.M.; software, F.H.; validation, B.M., D.A., M.M., H.Z., and H.H.; formal analysis, F.H. and B.M.; investigation, B.M.; data curation, F.H. and B.M.; writing—original draft preparation, F.H. and B.M.; writing—review and editing, B.M., M.M., and B.M.; supervision, B.M., D.A., M.M., H.Z., H.H., and B.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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